TRANSPORTATION OF BED LOAD AND ITS FORMATION FOR INBANK FLOW: A PHYSICAL MODELLING APPROACH

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Abstract: Floods hit various states in Malaysia and caused damage to properties, infrastructures, human suffering and even loss of lives. Frequent flood incidents and soil erosion are reported which lead to sedimentation problems in the drainage and river systems due to urbanisation. It is important to understand the sedimentation process and the behaviour of bed forms in the water course for post-flood events. However, it is risky and dangerous to conduct field study during occurrence of flooding. Laboratory study has been chosen as an alternative to fulfill the objectives. Experimental investigations on the bed load transport and bed forms in rectangular open channels have been undertaken. Small and large scale physical models are used in the laboratory. The effects of flow on mobile sandy bed channel and bed load transportation are studied by using a modified flumes with an asymmetric straight compound channel. However, the findings on rate of transport and bed formation for non-flooding cases are presented in this paper. It is found that the bed formation profiles for both channels are different due to scale and flume characteristics. The bed forms, erosion and deposition processes are significantly influenced by the water velocity in the channel. The bed forms observed for large flume are repeating ripples and dunes; meanwhile variable of ripples are observed in small flume.

Keywords: *Straight channel, inbank flow, velocity distribution, bed load transport, bed formation*

1.0   Introduction

The structure of the flow in mobile bed channels are more complex than in non-mobile bed channels. In order to understand the more complex hydraulic characteristics of mobile bed compound channel flow, a basic understanding of inbank flow is necessary. Such understanding is important because it elucidate what happens in alluvial rivers especially under normal flow conditions. The mobile bed data are more difficult to obtain than the corresponding data for rigid boundary channels. The presence of the bed

forms led to much greater variability in water surface slope, bed load rate and channel dimensions than anticipated (Knight *et al.*, 1999).

The morphology of alluvial channels such as sandy bed reflects a complex interaction of flow, channel geometry, energy dissipation and sediment transport. The transport of non-cohesive sediments during steady uniform flow is a complex process, which becomes more complex to be described mathematically during overbank flow because of the interaction between floodplain flow and main channel flow (Karamisheva *et al.*, 2005). Bed load transport, which results from the motion of particles rolling, sliding or traveling in a succession of low jumps or saltations along the bed of a stream, is of fundamental importance for river morphodynamics. It may indeed represent an important fraction of the total sediment flux transported in a river (up to 60 %), especially in gravel bed rivers (Métivier *et al.*, 2004; Meunier *et al.*, 2006; Liu *et al.*, 2008).

Many aspects of morphologic changes in rivers are governed by bed load transport, including bank erosion, bed forms and the rate at which the river incises relief (Yalin and da Silva, 2001). Bed load transport rates depend on the near bed flow characteristics and sediment properties, such as shear stress, surface roughness, and particle size, density, and shape. The bed form of mobile sandy bed channels reflects a complex interaction among flow hydraulics, channel geometry, energy dissipation and sediment transport. The bed will deform under the action of flow, changing its roughness, and then affecting the flow itself (Knight and Brown, 2001). It is important to understand the sediment transport process and the bed formation in order to maintain the rivers as safe from the sedimentation problems.

The approach proposed by van Rijn (1984*a*, 1984*b*, 1984*c*) gave very good predictions of the roughness effects of the mobile bed. Zang *et al.* (2010) and Ali *et al.* (2012) also stated that the roughness of non-mobile beds is noticeably less than those of mobile beds. Ackers (1992) predicted that the sediment transport will increase in most rivers up to bankfull discharge, but the sediment transportation process may diminish with further increase in discharge and roughness on overbank condition. Ayyoubzadeh (1997), Atabay *et al*. (2005) and Tang and Knight (2006) investigated and found that a very similar way to what Ackers predicted.

Channels can be considered as simple channels during normal flow. Investigations on the bed load transport and bed forms in simple channels have been undertaken in the laboratory. The effects of uniform sand bed channels are studied by using small and large flumes. The aim of study is to enhance knowledge on the sedimentation and bed forms in the water course during pre-flood events.

2.0   Experimental Study

The research comprised of two parts: small and large flumes which are tested in the Hydraulics Research Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru.

2.1   Small Flume

The small scale study utilised a modified 4 m long and 0.6 m wide flume as illustrated in Figure 1. A physical model consisted of a rectangular main channel with 0.2 m wide and 0.05 m deep and a single floodplain of 0.4 m wide. Figure 2 displays the cross-section of the modified flume. The bed slope of channel is fixed to 0.2 % and uniform graded sand with a d_{50} of 0.8 mm is used as its bed material. The water depth and level of sand surface in the main channel are measured by using a digital point gauge. The discharge in the main channel has been calculated using the values of the measured velocity through the conventional "mid-section" method. The velocities are measured by using Nixon Streamflow 430 miniature current meter.
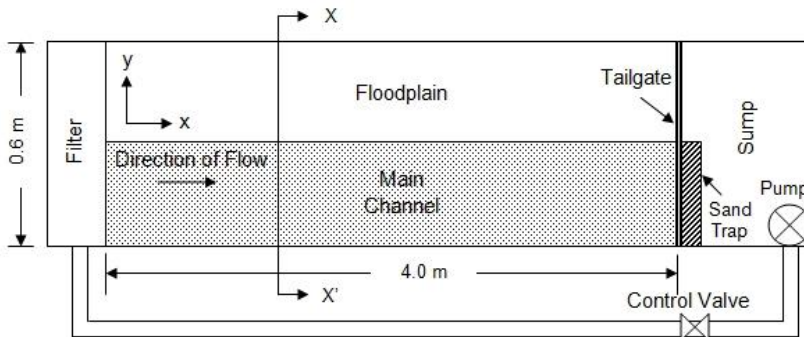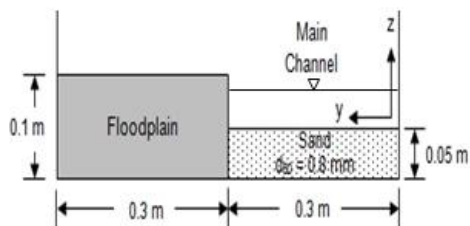

Figure 1: Plan view of small flume

Figure 2: Cross-sectional view of small flume

A sand trap is placed at channel downstream to collect sediment which has been transported in the main channel. The transported sediment is collected within 2 minutes interval for duration of 40 minutes. After weighing the sediment is placed back into the main channel at the inlet. The experiment is run at the required water depth until the equilibrium bed form has developed. The mass of sediment transport is determined using a digital weighing scale. Equation (1) is used to determine the sediment transport rate.

$$q_s = \frac{m_s}{t} \tag{1}$$

where q_s is rate of sediment transport (g/s); m_s is mass of sediment transported (g) and t is sampling time (s).

2.2   Large Flume

A 12 m long and 1.0 m wide large flume is constructed in laboratory. Figures 3 and 4 illustrate layout of experimental set-up and the cross-sectional configuration of the flume. The geometrical parameters are equal floodplain width, B_f and main channel width, B_m of 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 0.1 % and uniform graded sand with d_{50} of 0.8 mm is also used as bed material.

A portable flow meter is installed to measure discharge in the channel. The water depth in the flume is controlled by an adjustable tailgate located at downstream. A digital point gauge attached on a special mobile carrier is used to measure the water depth and bed forms level. A sand trap is placed at channel downstream to collect sediment that passed through the sediment pipe. Every 15 minutes the sieve is removed, and replaced with another sieve. The collected sediment is then weighed to determine the mass of bed material transported. The sediment is placed back into the main channel at the channel inlet. The sediment transported is collected over duration of 6 hours in each case. The experiment is left to run continuously for more than 12 hours and the water surface level evaluation is checked regularly until representative bed forms have been developed. At higher flow depth, it is quite difficult to ensure that the flow is uniform due to fluctuations of the water level. Additionally, the development of bed forms varied dramatically with time; taking sometimes of longer time scales (Ismail, 2007; Milian, 2008).

Point velocities are measured using Nortek Vectrino+ Acoustic Doppler Velocimeter at a frequency of 100 Hz over 70 mm^3 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*. (2007) stated that frequency of 50 Hz within 30.0 s is enough for acquisition of data velocity. For most turbulent statistics, sufficient record length for measurement

is 60 to 90 s (Czernuszenko *et al.*, 2007). The transverse interval distance for velocity measurement is 0.02 m and it varies in vertical direction.
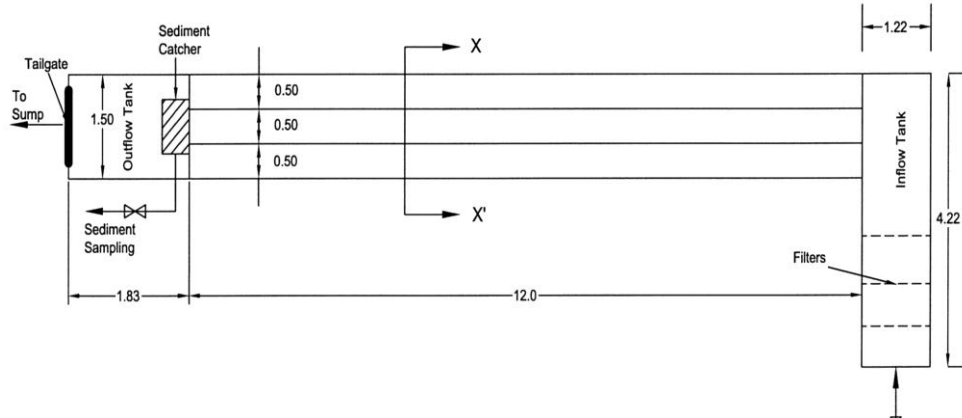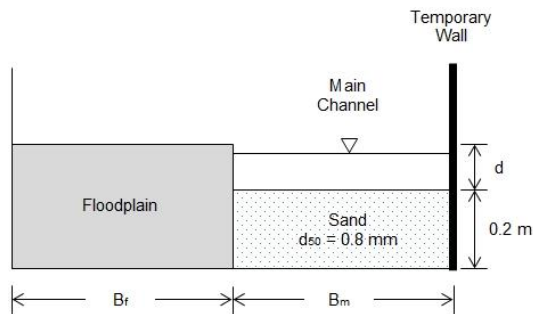
Figure 3: Layout of large flume

Figure 4: Cross-sectional view of large flume

3.0   Results and Discussion

To apply uniform flow theory in the analysis, the uniform flow has been achieved where slope of water surface (S_w) is equal to bed slope of channel (S_o) at all time. The results of bed load transport rate and bed formation are discussed separately based on the scale of physical model.

3.1   Small Flume

The analyses of experiment data for the small flume concentrate on the flow condition, depth-averaged stream-wise velocity, sediment transport and bed formation. They are discussed as follows.

3.1.1   Flow Conditions

The Froude (Fr) and Reynolds (Re) numbers are used to determine the ambient flow condition in the experiment. The Fr and Re are determined via Equations (2) and (3):

$$Fr = \frac{u}{\sqrt{gH}} \tag{2}$$

$$Re = \frac{uR}{v} \tag{3}$$

where u is the mean stream-wise velocity in main channel (m/s); g is the gravitational acceleration (m/s^2); H is the mean water depth in main channel (m); R is the hydraulic radius (m) and v is kinematic viscosity of water (m^2/s) at temperature of 27° C. The calculated Re is 13,200 and Fr is 0.46. Therefore, the regime of flow is classified as sub-critical with turbulent condition.

3.1.2   Depth-averaged Stream-wise Velocity

The depth-averaged stream-wise velocity is normalised by dividing U_d to U_m. U_d is depth-averaged velocity and U_m is the cross-sectional mean velocity. Figure 5 shows transverse distribution (y/B) of the (U_d/U_m) where y is transverse distance, B is total channel width. It shows that the patterns of the stream-wise velocity at the different longitudinal locations (x/L) are almost similar. x represents longitudinal distance and L represents total length of the channel. It clearly shows that the maximum flow velocity occurs in the centre of the main channel region and decrease towards the channel walls. The bed form profile significantly affected by the water flow. The bed forms also contribute an additional roughness which indirectly reduces the velocity of water along the channel.

From Figure 5, the higher value of normalised depth-averaged stream-wise velocity obtained is 1.10 at the point of transverse distribution (y/B = 0.50); meanwhile, the lowest normalised of stream-wise velocity is 0.79 at the transverse distribution (y/B = 0.10) which are found to be at longitudinal location of (x/L = 0.69). The differences in depth-averaged stream-wise velocity along the channel are due to the different in depth and flow resistance which is caused by bed form profiles.
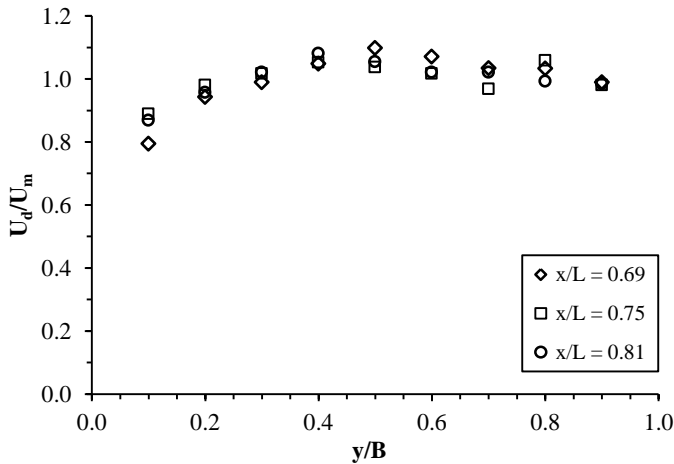
Figure 5: Transverse distribution of U_d/U_m along the small flume

3.1.3   *Sediment Transport*

The transported sediments were collected every 2 minutes for duration of 40 minutes. Figure 6 shows the normalised temporal pattern of mass of sediment transported where m_s is mass of sediment transported, $(m_s)_{max}$ is total mass of sediment transported, t is time taken for collected sediment and t_{max} is total time taken for collected sediment. Figure 7 illustrates the temporal pattern of sediment transport rate.

The results also show fluctuations arising from the change in bed elevation caused by the bed forms and dune mitigation rate which similar results as the large flume study. The bed load transport mass and rate is also fluctuating, against the mean value. Based on Figure 6, the maximum and minimum normalised mass of sediment transported $[m_s/(m_s)_{max}]$ obtained are 0.083 and 0.025 at point of t/t_{max} equal to 0.10 and 0.90; where the mean value of $[m_s/(m_s)_{max}]$ is 0.050. Meanwhile, Figure 7 exhibits the maximum and minimum sediment transport rate obtained are 14.0 and 4.17. This indicates that the sediment transport is maintained reasonably well in the equilibrium condition same as mentioned in large flume study.
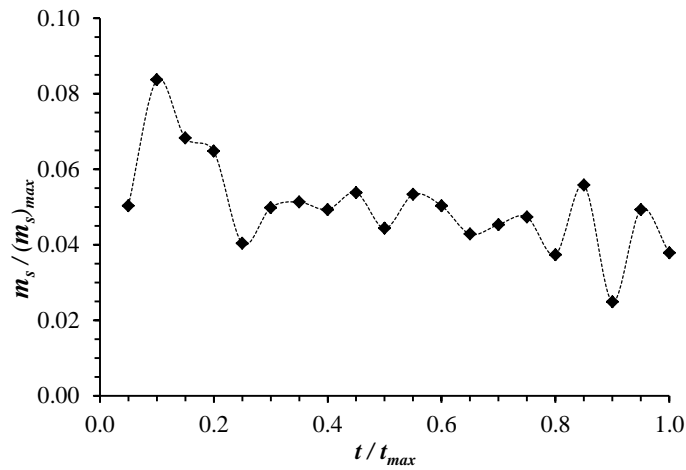
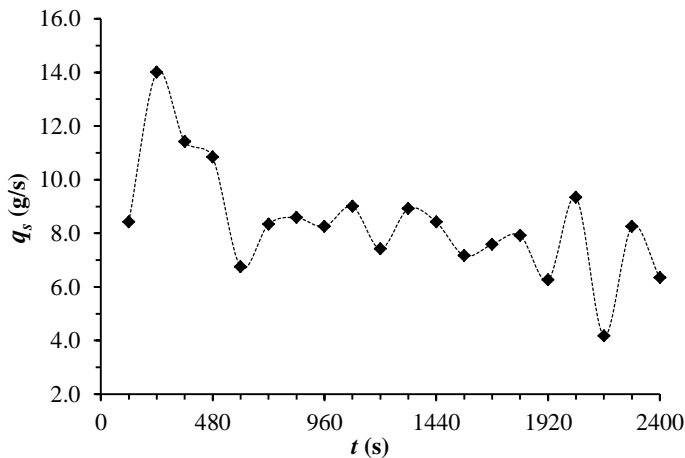Figure 6: Normalised temporal pattern of mass of sediment transported

Figure 7: Temporal pattern of sediment transport rate

3.1.4   Bed Formation

The visualization of bed contour in the main channel is also plotted using the Tecplot 360 software, as illustrated in Figures 8. Negative contour values indicate erosion while positive values indicate deposition in millimeter unit (mm). The bed forms indicate that erosion clearly occur at most of part in the main channel. The sands are covered with irregular bed forms consisting of ripples along the channel. In order to indicate the correlation between changes of sand bed level and stream-wise velocity distribution, it

demonstrates that the sand bed level mostly erode in the middle of main channel where the maximum velocity observed in the centre region of the main channel. The flow velocity which remained in the main channel also tends to influence the higher sediment transportation and changes of sand bed level. The maximum level of eroded sand bed formed is 10 mm.
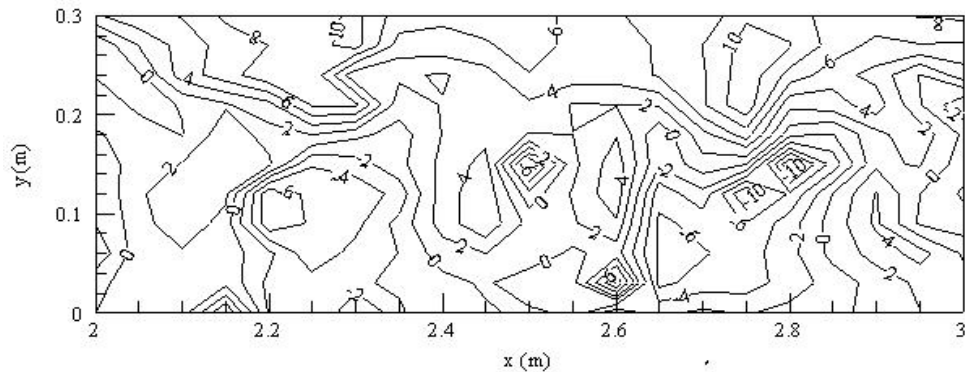

Figure 8: Plan view of bed profiles along the main channel

3.2   Large Flume

The analysis of experiment data for the large flume cover on the flow condition, depth-averaged stream-wise velocity, sediment transport and bed formation are discussed as follow:

3.2.1   Flow Conditions

The Froude (Fr) and Reynolds (Re) numbers are determined via Equations (2) and (3) as shown in previous section. The calculated Re is 32,900 and Fr is 0.41. Therefore, the regime of flow is classified as sub-critical with turbulent condition.

3.2.2   Depth-averaged Stream-wise Velocity

The depth-averaged stream-wise velocity is normalised by dividing the depth-averaged velocity (U_d) to the cross-sectional mean velocity (U_m). Figure 9 shows transverse distribution (y/B) of the (U_d/U_m). y is transverse distance, B is total channel width. The observed velocity at the different longitudinal locations (x/L) along the flume is almost fluctuates. x is longitudinal distance and L is total length of the channel. However, the patterns of the stream-wise velocity at (x/L = 0.38) and (x/L = 0.50) are quite similar. Meanwhile, the stream-wise velocity at (x/L = 0.63) is slightly higher than other

longitudinal location. This is due to the deposition of sediment at the channel downstream resulting in shallow bed section.

From illustration, the higher value of normalised depth-average stream-wise velocity obtained is 1.21 at (x/L = 0.38) and 1.14 at (x/L = 0.50) which are found to be at the same point of transverse distribution (y/B = 0.44). Meanwhile, at (x/L = 0.63), the higher velocity value is found to be 1.20 at the transverse distribution (y/B = 0.64). The differences in depth-averaged stream-wise velocity along the chainage are 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 to two sources, described by Chang (1988) as grain resistance of channel bed material and form resistance or form drag due to the shape of channel bed forms. 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 sedimentation and erosion phenomena. 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.
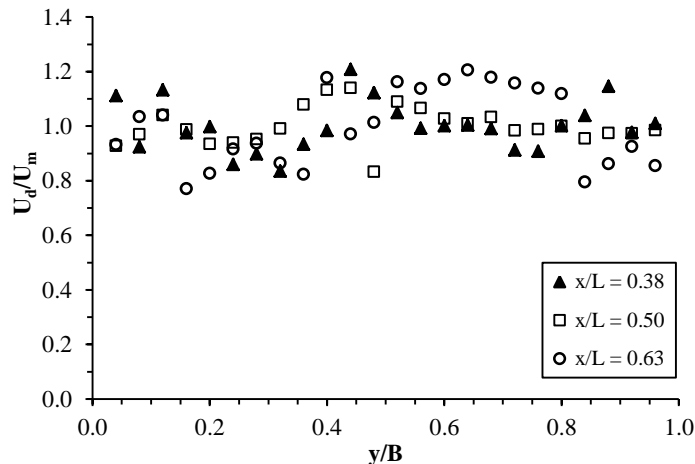

Figure 9: Transverse pattern of U_d/U_m along the large flume

3.2.3   Sediment Transport

The transported sediments are collected every 15 minutes for duration of 6 hours. The mass of sediment transport is weighted using a digital scale. The sediment transport rate must be 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 (Spooner, 2001). The sediment

transport rate is directly related to the velocity in the main channel and therefore, the reduction of the sediment transport rate means a reduction of velocity (Ismail, 2007). Tang and Knight (2006) stated that the sediment transport rate decreases even further as the roughness of the channel increase.

Figure 10 displays the normalised temporal pattern of mass of sediment transported. m_s is mass of sediment transported, $(m_s)_{max}$ is total mass of sediment transported, t is time taken for collected sediment and t_{max} is total time taken for collected sediment. Figure 11 demonstrates the temporal pattern of sediment transport rate. It shows fluctuations arising from the change in bed elevation caused by the bed forms and dune mitigation rate.

Figures 10 and 11 show that bed load transported mass and rate are fluctuating, against the mean value. From illustration of Figure 10, the maximum and minimum normalised mass of sediment transported $[m_s/(m_s)_{max}]$ obtained are 0.048 and 0.036 at t/t_{max} 0.17 and 0.58; where the mean value of $[m_s/(m_s)_{max}]$ is 0.042. Meanwhile, Figure 11 presents the maximum and minimum sediment transport rate obtained are 4.32 g/s and 3.21 g/s respectively. This indicates that the sediment transport is maintained reasonably well in the equilibrium condition. A similar result is reported by Knight and Brown (2001).
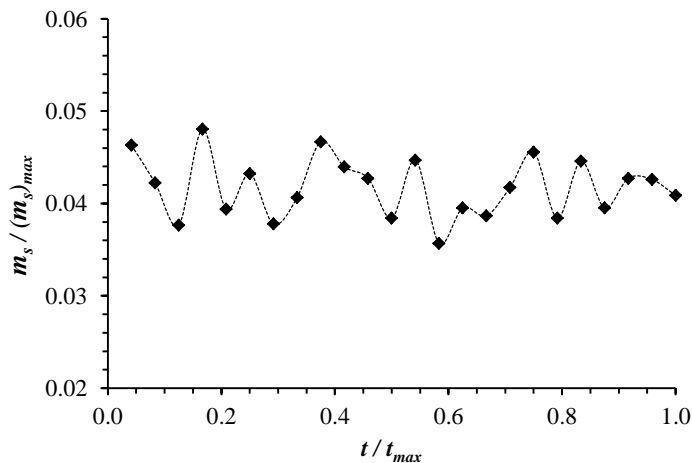

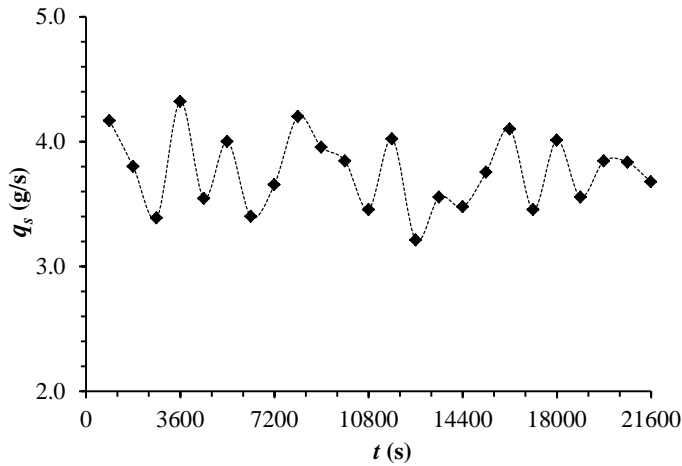Figure 10: Normalised temporal pattern of mass of sediment transported

Figure 11: Temporal pattern of sediment transport rate

3.2.4   Bed Formation

The bed form morphology is observed with the determination of visualizing and understanding the flow phenomena occurrence on the bed channel. Channel bed formation occurs due to flow velocity in the main channel. During the flow, sedimentation and erosion phenomena occur and cause the changes of sand bed elevation. Most of sand erosion and sedimentation are governed by the flow velocity along the main channel. The levels of sand surface in the main channel are measured by using a digital point gauge. The visualization of bed contour in the main channel is plotted using the Tecplot 360 software, as illustrated in Figure 12. The contour plots show the measured scour depth in millimeter unit (mm). The negative values indicate erosion while positive values represent deposition.

In order to express the correlation between changes of sand bed level and stream-wise velocity distribution, the bed forms show that erosion apparently occur in the upstream region and then slightly occur at the downstream area due to the energy of the flow velocity in the channel. It also shows that the sand bed level at the downstream part mostly 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 maximum level of eroded sand bed formed is 50 mm.
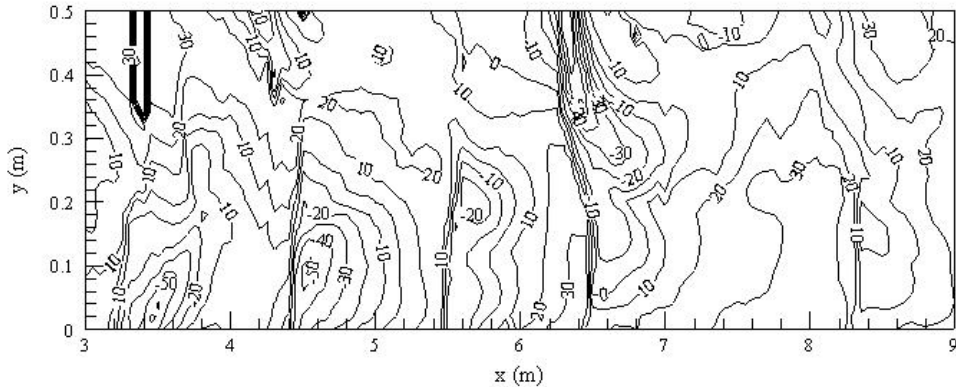
Figure 12: Plan view of bed profiles along the main channel

4.0   Conclusions

The hydraulics of simple channels with mobile bed has been investigated in the laboratory using small-scale and large-scale physical models. The behaviour of flow including flow conditions, depth-average stream-wise velocity distribution, sediment transport rate and bed formation are inspected in order to enhance knowledge on the fluvial problem before flooding. The conclusion can be drawn from the findings are:

(i)   The channel bed forms and sediment transportation as well as erosion and deposition processes are significantly influenced by the flow velocity in the channels. The sediment transport rate must be 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.

(ii)   The mass and rate of sediment transport for both flumes are fluctuated against the mean value and arising from the change in bed elevation caused by the bed forms and dune mitigation rate. It indicates that the sediment transport is maintained reasonably well in the equilibrium condition.

(iii)   The percentage difference of normalised mass of sediment transported $[m_s/(m_s)_{max}]$ values for the small flume is almost 70 % which relatively higher compared to 25 % for the large flume.

(iv)   The sediment transport rate for the small flume is greater than the large flume which is found to be almost 70 % of differences. It is due to number and interval time taken of collected transported sediment sample.

(v)   The bed form profiles for both flumes are quite different due to scale and flume characteristics.

(vi)   The bed form profiles observed for large flume are repeating ripples and dunes; meanwhile variable of ripples are observed in the small flume.

5.0   Acknowledgements

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