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Hydraulic and morphological patterns in a riparian vegetated sandy compound straight channel

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Abstract. Emergent vegetation or trees are important riverine features and essential in hydraulic engineering including flood management and river restoration. Clearing up trees along river banks has been pointed out as a contributing factor to the severity of flood damages including financial losses and even fatalities. Thus, the effect of riparian vegetation on river flow must be clearly understood. The hydraulics and morphological patterns in a riparian vegetated sandy compound straight channel were carried out in the Hydraulics Laboratory, School of Civil Engineering, Universiti Teknologi Malaysia. Two-line steel rods with tandem and staggered arrays to simulate as rigid emergent vegetation were placed along the riparian zone of an asymmetrical straight channel. The Manning's n, depth-averaged velocity, boundary shear stress and morphological changes during shallow and deep floods are discussed in this paper. The findings prevailed that the staggered array riparian vegetation generated 4.5% flow resistance higher than the tandem array. The vegetation also altered velocity distribution which contributed to the boundary shear stress patterns in a compound straight channel. The flow velocity profiles were also related to the morphological changes in the channel.

1. Introduction

Deforestation activities on floodplain areas for agricultural, commercial or housing purposes have raised the issues of flood risk and flood protection [1]. Vegetation along river banks were pointed out to play important roles for river banks stabilisation, erosion prevention, habitat creation and riparian buffer zones development for flood protection [2]. Generally, vegetation may be regarded as kind of surface roughness which increases the flow resistance, alters velocity distribution, affects the conveyance of rivers, raises water levels and also influences a transportation rate of sediment in rivers [3].

The hydraulic of flood flow in open channel is characterised by a complex flow structure due to the interaction between the main channel and floodplain flows, lateral momentum transfer and secondary flows [4]. River flow, sediment transport and morphological processes are among the most complex and least understood processes or phenomena in nature [5]. Floodplain and main channel have their own characteristics such as roughness which depends on their type of surface. The local friction factor is a parameter that essentially relates the local boundary shear stress to the depth-averaged velocity [6]. The

riparian vegetation plays a significant impact on the transverse distributions of depth-averaged velocity and boundary shear stress in the in the compound channels [7, 8].

The flow structure and the scour bed depend on the flow conditions. Various kinds of bed profiles are directly influenced to the variability of velocity distributions in the main channel. Japanese researchers reported that the secondary streamwise vorticity and bed profiles affected each other, where the secondary currents tend to form sandbars due to erosion and deposition processes [9]. Therefore, it is important to further understand influence of the riparian vegetation on the river hydraulics. Experimental investigations on the hydraulic and morphological patterns in a riparian vegetated sandy compound straight channel were undertaken.

2. Experimental methodology

The experiments were carried out in a 12 m long flume with 0.5 m wide and 0.1 m deep rectangular main channel and a 0.5 m wide floodplain in Hydraulics Laboratory, Universiti Teknologi Malaysia. The flume bed was set at a gradient of 0.1%. Uniform graded sand with a mean diameter, d_{50} of 0.8 mm was filled as bed material in the main channel. The purpose of using uniform graded sand in the research was to minimise the "sheltering" and "hiding" effects. As bed forms propagated to the downstream, sediment moved from the ridge 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 [10].

Steel rods with 5 mm diameter were used as artificial resistance elements in this study. The two-lined rods were placed in staggered arrays along the riparian zone to simulate as *2d* closed spacing emergent floodplain vegetation where *d* represented the rod diameter. These resistance elements were placed at the edge along the floodplain with a distance between 4 m to 8 m from the channel inlet. The layout of experimental set-up and the cross-sectional configuration of the channel are illustrated in figures 1 to 2.

The laboratory experiment was carried out for more than 24 hours. The water surface level was checked regularly until an equilibrium bed forms have been developed. The development of bed forms varied with time. A re-circulating flume system was used in the study and the discharge was measured using a Portaflow PF330 flow meter. Flow depth and bed morphological levels were measured using a digital water surface profiler with an accuracy of ± 0.1 mm attached on a mobile carrier. Meanwhile, the flow velocity was measured using a Nortek Vectrino+ Acoustic Doppler Velocimeter (ADV) with a sampling rate of 100 *Hz*. The transverse interval distance for velocity measurement was 2 cm and varied in vertical distance.
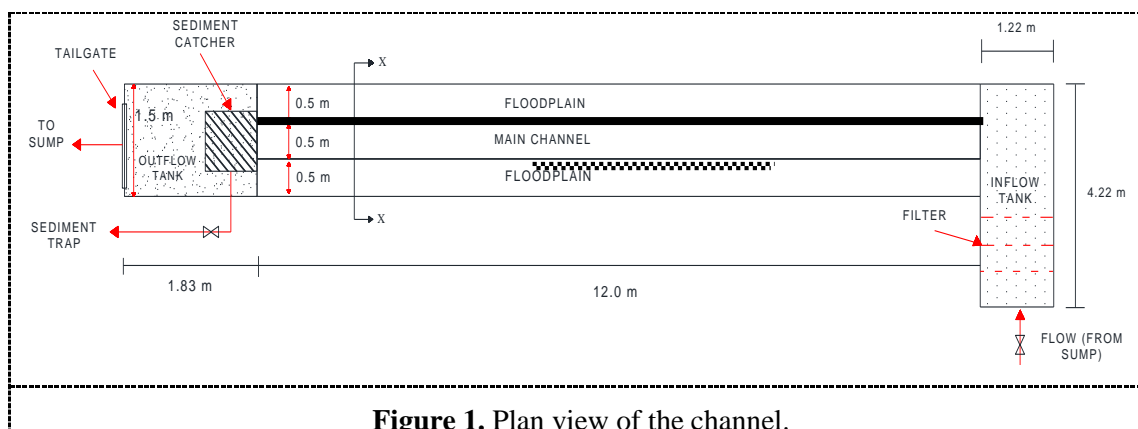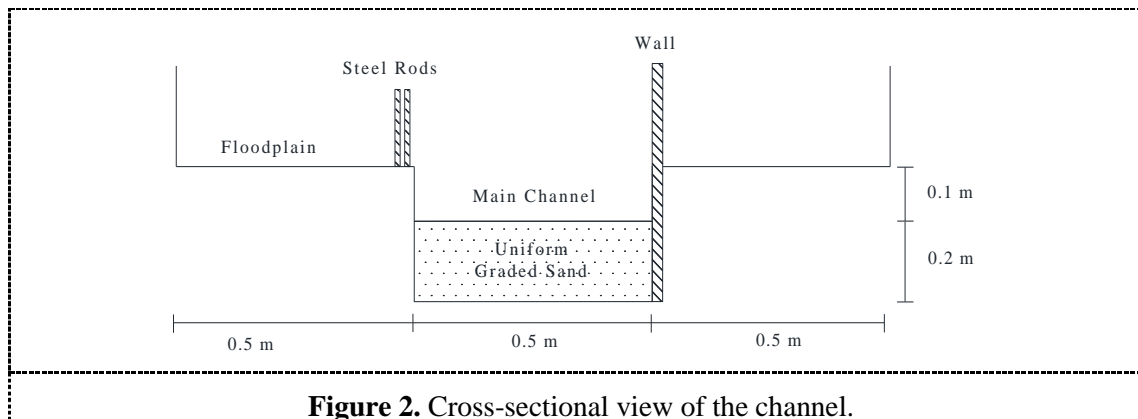

Figure 1. Plan view of the channel.

Figure 2. Cross-sectional view of the channel.

3. Results and discussion

The experimental investigations were conducted under uniform flow condition. *DR* is the relative depth = $(H - d)/H$. *DR* of 0.30 and 0.50 were represented shallow and deep inundation cases. For both relative depths, the calculated Reynolds number (*Re*) exceeded 2,000 and the Froude number (*Fr*) was less than unity. Hence, the regimes of flows were classified as sub-critical with turbulent condition. Table 1 summarise the details of experimental cases in this study. The presence of vegetation along the river bank decreased the water flow capacity and increased the water level in the channel. The Manning's *n* increased as the *DR* increased. The Manning's *n* for Case B was 9.2% higher than non-vegetation of Case A. Meanwhile, the Manning's *n* for Case C was 4.5% and 14.3% higher than Cases B and A, respectively. Therefore, it is noticed that the staggered arrangement vegetation also had more impact on flow reduction than tandem arrangement. A similar trend on the roughness effects of vegetation in the compound channel was reported by Jumain *et al*. [10].

Table 1. The details of experimental cases.

Case	Condition of floodplain	*DR*	*H* (m)	*Q* (m³/s)	Manning's *n*
A	Non-vegetated	0.30	0.1430	0.026	0.019
		0.50	0.1945	0.045	0.023
B	Vegetated in Tandem Arrangement	0.30	0.1442	0.026	0.020
		0.50	0.2093	0.045	0.026
C	Vegetated in Staggered Arrangement	0.30	0.1465	0.026	0.021
		0.50	0.2155	0.045	0.027

3.1. Depth-averaged velocity

Generally, a primary velocity in open channel varies with its location. The velocity is low near the channel boundaries (i.e. wall and bed). It is also largely dependent on flow condition and the geometrical shape of the channel. In this study, the depth-averaged velocity U_d was computed using equation (1) where the primary or streamwise velocity was averaged over the flow depth. The transverse distribution of depth-averaged velocity for various cases at the middle of channel length were plotted for *DR* of 0.30 and 0.50. The floodplain is located between $y/B = 0$ to 0.5, while main channel is located between $y/B = 0.5$ to 1.0. Therefore, $y/B = 0.5$ is the main channel and floodplain interface. *y* represents transverse distance and *B* is total channel width.

$$U_{d(y)} = \frac{1}{H(y)} \int_0^{H(y)} U dz \qquad (1)$$

Figures 3 and 4 depict the transverse distributions of depth-averaged velocity U_d in compound straight channels for *DR* of 0.30 and 0.50, respectively. It can be clearly seen that the U_d in non-vegetated Case A was the highest compared to vegetated cases for both *DR*. The maximum U_d in main channel for

Case A was 0.34 m/s compared to 0.32 m/s and 0.29 m/s for Cases B and C at shallow *DR* of 0.30. When the *DR* raised to 0.50, the flow was distributed more uniform between main channel and floodplain particularly for non-vegetated of Case D. More floodplain flows took place in the compound channel as the *DR* rose. The maximum U_d of 0.37 m/s was observed in Case A, which was 10% higher than the maximum U_d at shallow *DR* of 0.30. A sudden drop of velocity (shear layer) took place for both *DR* at the main channel-floodplain interface and vegetated zone. It was also obvious that the shear layer increased as the floodplain roughened by vegetation in Case B and Case C. The rods had limited the penetration of main channel flow into the floodplain and lowered the floodplain velocity. This was normally due to the flow retardation effect by the floodplain vegetation in the channel. For details on the cross-sectional distribution of streamwise velocity in a riparian vegetated compound channels are presented in Jamal *et al.* [11].
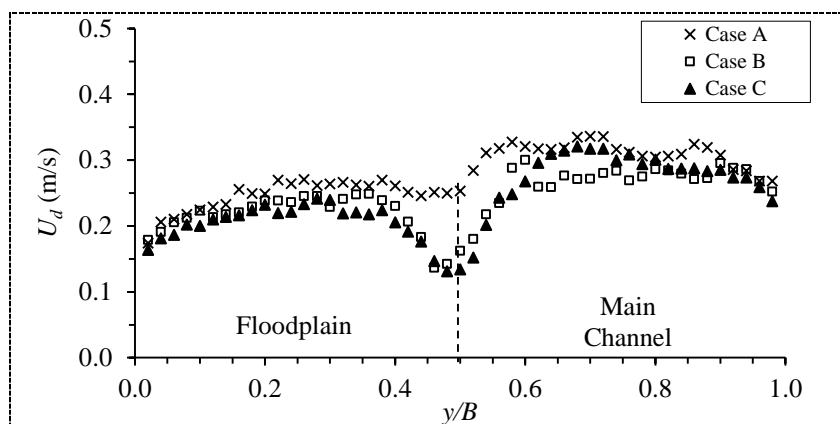

Figure 3. Transverse distribution of depth-averaged velocity U_d in compound straight channel at *DR* of 0.30.
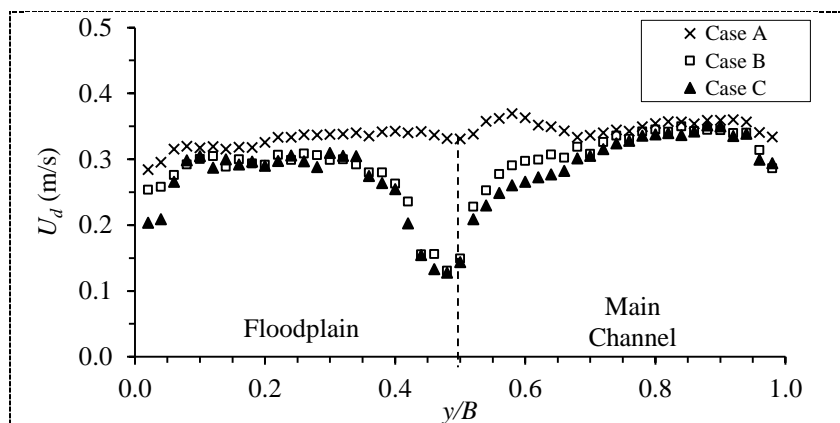

Figure 4. Transverse distribution of depth-averaged velocity U_d in compound straight channel at *DR* of 0.50.
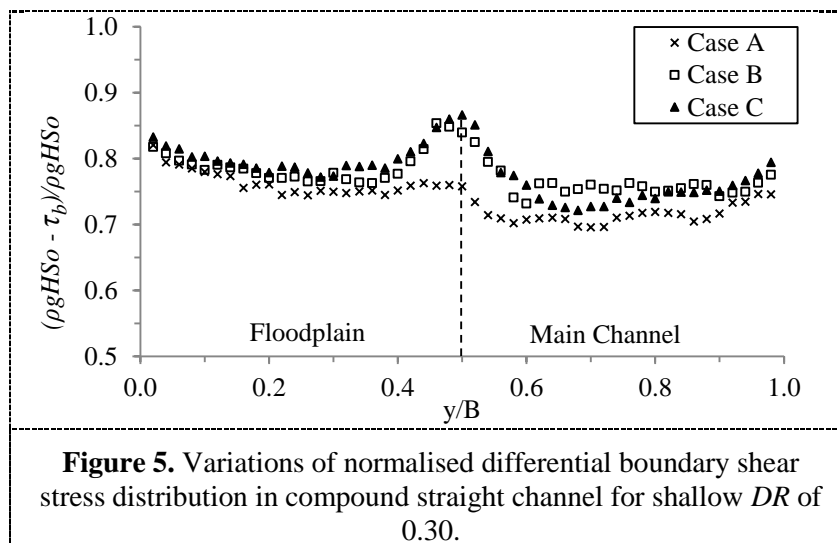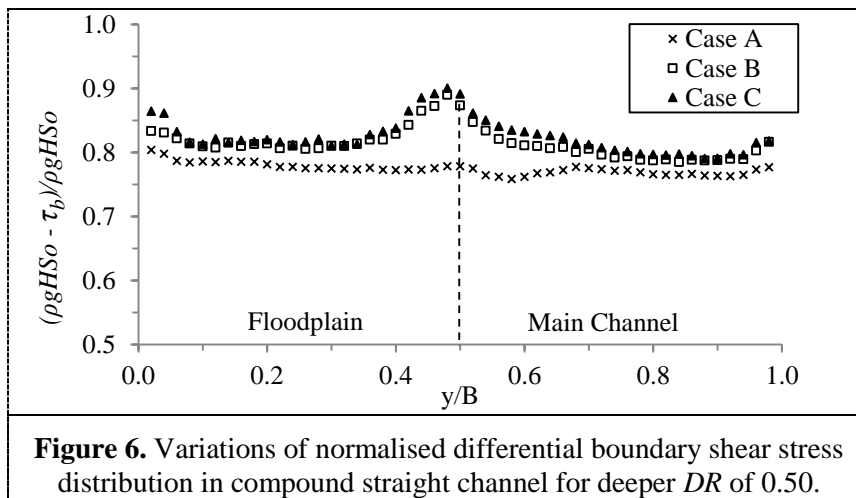
3.2. Boundary shear stress

Boundary shear stress is an important prediction parameter of sediment transport rates in rivers. The boundary shear stress τ_b in the compound straight channel in this study was measured using Preston tube method. Shear stress in a compound channel is strongly governed by interaction between main channel and floodplain flows due to prevailing of different their hydraulic conditions and the cross-sectional shape. Velocity distribution influences the distribution of boundary shear stress in compound

channels. The distributions of normalised differential boundary shear stress $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ in mobile bed compound channels for *DR* of 0.30 and 0.50 are presented in figures 5 and 6. A small value of $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ represents large boundary shear stress in the channel. This was observed in Case A of non-vegetated compound channel.

In a shallow *DR* of 0.30, the maximum $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ value was 0.87 as observed in Case C with staggered array vegetation on the floodplain. Meanwhile, the minimum $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ value was 0.70 in Case A which was observed in the main channel. The values of $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ were seen more scattered in the main channel section compared to floodplain section. It was directly related to the morphological bed changes in the channel. Another feature was that the $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ value was high near to the channel boundaries (i.e. wall and bed). This was due to the flow resistance produced by roughness of the channel boundaries as highlighted by Zeng *et al.* [12].

For *DR* of 0.50, the normalised differential shear stress was distributed more uniformly in main channel and floodplain as presented in figure 6. Larger value of $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ represents the smaller τ_b in the compound channel. The maximum values of $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ were 0.80, 0.89 and 0.90 for Case A, Case B and Case C, respectively. It was found that the $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ in Cases B and C were 11.2% and 12.5% higher than Case A. However, the discrepancy of $[(\rho g H S_o - \tau_b)/\rho g H S_o]$ values observed between tandem and staggered array vegetation cases was only 1.2%. The percentage difference was not too high since the study concentrated on only 4 m of two-line emergent floodplain vegetation located at a distance *x/L* of 0.33 to 0.67 in the channel. A significant result probably could be seen if vegetation was placed on whole floodplain section.

Figure 5. Variations of normalised differential boundary shear stress distribution in compound straight channel for shallow *DR* of 0.30.

Figure 6. Variations of normalised differential boundary shear stress distribution in compound straight channel for deeper *DR* of 0.50.

3.3. Bed morphology

River morphodynamics is defined as the sum of complex interactions between the water flow and sediment in the riverine environment. The visualisation of sand bed morphology in this study was observed to understand the flow behaviour on the transportation of sediment in compound straight channels. Figures 7 to 9 show the normalised longitudinal bed level changes ($\Delta Z/Z$) at the middle main channel section for *DR* of 0.30 and 0.50. ΔZ is the bed level changes, Z is initial or original bed level, x is longitudinal distance and L is total length of the channel.

It was noticed that various patterns of bed profiles for each case were due to the difference of velocity along the main channel. Most equilibrium bed level was reached at the middle main channel section which located at x/L of 0.45 to 0.75 along the channel length. This was visible in all cases for both relative depths. The sand bed in the upstream channel was eroded and transported along the main channel at shallow *DR* of 0.30. The maximum ($\Delta Z/Z$) was 16.1% which was observed in Case A. Meanwhile, the maximum ($\Delta Z/Z$) in Cases B and C were 9.9% and 7.8%. This implies that the riparian vegetation increases the flow resistance which leads to the velocity reduction of the channel flow.

It was also found that the unstable (inequilibrium) condition of sand bed level occurred at locations x/L of 0.25 to 0.35 which was closer to the inlet flume for all cases at *DR* of 0.50. The pattern of main channel bed profiles for Case B was also found to be slightly different from other cases. It was due to bed-load flux produced by high turbulent flow from inlet flume. Similar results reported by Garcia *et al.* [14] where the highest bed-load fluxes occur as water depth and discharge increased. It was found that the different patterns of main channel bed morphology for each case were due to velocity variation along the channel.
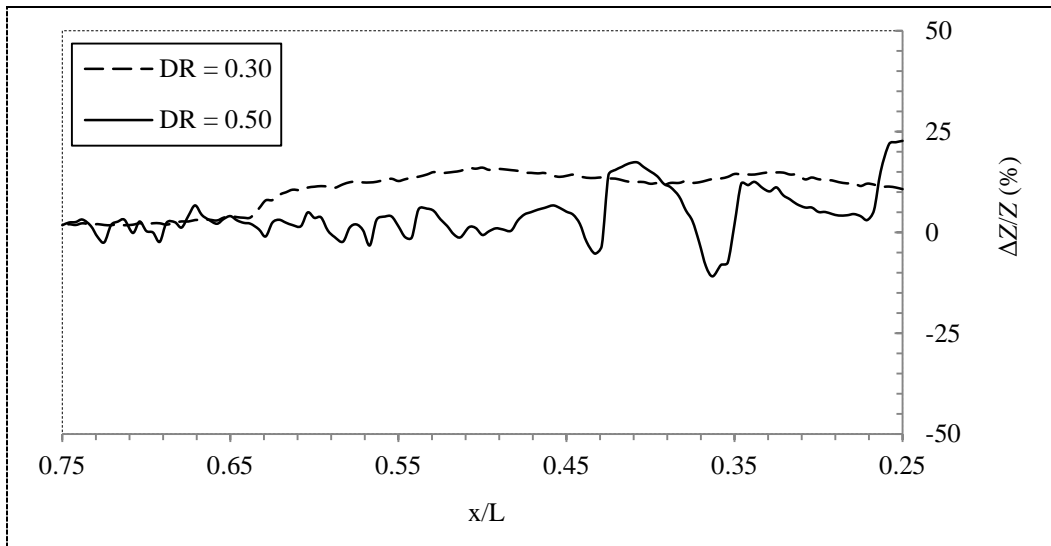
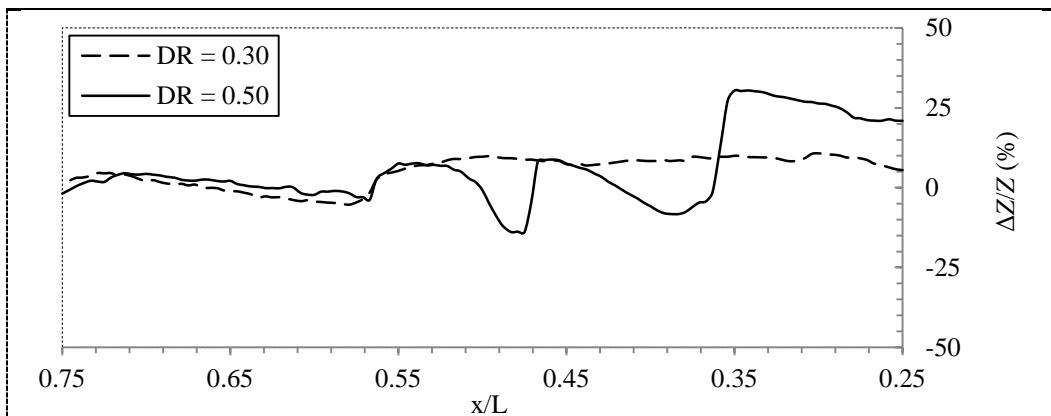**Figure 7.** Longitudinal cross-section of main channel bed profiles for Case A at *DR* of 0.30 and 0.50.

Figure 8. Longitudinal cross-section of main channel bed profiles for Case B at *DR* of 0.30 and 0.50.
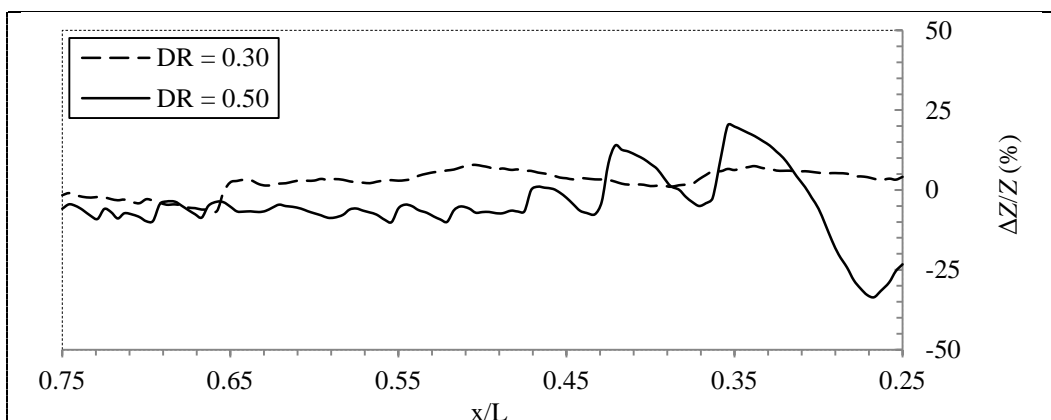

Figure 9. Longitudinal cross-section of main channel bed profiles for Case C at *DR* of 0.30 and 0.50.

4. Conclusion

The hydraulic and morphological patterns in a riparian vegetated sandy compound straight channel has been experimentally investigated. The conclusion can be drawn from the findings are: (i) the presence of riparian vegetation cause a sudden drop of velocity at the main channel-floodplain interface and vegetated zone due to the flow retardation effect by the floodplain vegetation in compound straight channels, (ii) The distributions of normalised differential boundary shear stress influenced by the velocity structure where shear layer and free shear took place near the main channel-floodplain interface and also vegetation zone, (iii) the vegetation also limits the movement of main channel and floodplain flows which influences to the changes and formation of main channel bed profiles.

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