The effect of vegetation along cross-over floodplain edges on stage-discharge and sediment transport rates in compound meandering channels

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Abstract: - Experiments are conducted in compound meandering channels with partially vegetated floodplain to investigate the effect of vegetation on stage-discharge curves and sediment transport rates. Rectangular blocks are used as vegetation and placed along cross-over section for attempting to change floodplain velocity and flow interaction between the floodplain flow and the main channel flow in the meandering channels. Various densities of blocks are also used to investigate its effect on stage discharge curve and sediment transport rate. Stage-discharge curves for different block densities in the fixed bed case show quite different from those in the mobile bed case. Flow resistance is much higher in the mobile case than in the fixed bed case. The sediment transport rate with respect to discharge in different block density cases shows an interesting behaviour. Vegetation density along the floodplain edges significantly affects the behaviour of overall flow resistance and sediment transport rate in the compound meandering channel.

Key-Words: - vegetation, meandering channel, flooding, stage-discharge, sediment transport

Introduction

During the past decades, the conventional “flood control” ideology has evolved into a philosophy of “flood management”. An effective flood management program must consider environmental, recreational, and aesthetic issues in addition to flood control. Riparian vegetation has become an integral component of the flood channel. Vegetation stabilises stream banks, provides shade that prevents excessive water temperature fluctuations, supports wildlife and performs a essential role in nutrient cycling and water quality. In addition, vegetation is an important feature of many rivers, providing habitat for other organisms and enhancing amenity values for people. Emergent vegetation occurs commonly along the banks of river and artificial channels, both naturally and by design for erosion and habitat creation. The effect of such marginal vegetation on flow resistance has been investigated for straight channels but little known of the effects for meandering channels under either inbank or overbank flow conditions [1]. In meandering channels, secondary flow is one of important hydraulic parameters. Bathurst et al. defined secondary flow as a flow normal to that in the longitudinal flow direction [2]. Secondary currents distort the longitudinal velocity pattern and boundary shear stress distribution and are therefore important as they affect the flow resistance, sediment transport, bed and bank erosion and in turn influence the channel morphology. Previous researchers including Nezu and Rodi, Tominaga et al., Shiono and Knight and Tominaga and Nezu have investigated experimentally the secondary flows in compound channel [3][4][5][6]. They found that the secondary flow can be classified in two kinds. The first kind is driven by turbulence and the second one is driven by geometry of the channel. These secondary flows have a significant influence on the boundary shear stress distribution in the fluid system.

The extensive research on flow resistance in compound straight and meandering channels with fixed and mobile beds and, rough and smooth floodplains were carried out in Flood Channel Facility (FCF), HR Wallingford. In conjunction with this, the flow resistance in compound meandering channels has been investigated using smaller flumes such as Myers et al. [7]. They found that flow resistance in compound meandering channels is significantly more complex than simple channel. Myers et al. reported that the flow resistance values for meandering channels at high overbank depths are 50% greater than those for the straight channel with floodplains [7]. This indicates that there is an additional source of flow resistance occurred in meandering channels. Muto and Shiono studied the three-dimensional flow structures in meandering channels with overbank flow, based on velocity measurement using a two-component Laser Doppler Anemometer (LDA) [8]. They identified that the development of secondary flow for overbank flow structure is controlled by the flow interaction in the cross-over section. They also found that the generation mechanisms of secondary flow and turbulence are totally different from those for the straight compound channel and that most mean energy loss occurs along the cross-over region for the straight floodplain bank case. These differences are caused due to secondary flow and the interaction between the floodplain flow and the main channel flow. Thus the secondary flow is a dominant factor influenced in compound meandering channel. Secondary flows redistribute velocity and boundary shear stress and are also highly responsible for bank erosion process.

In general, the sediment transport processes in river channel is governed by number of factors. These factors can be classified into three categories such as characteristics of sediment properties, fluid and channel. In overbank flow condition, additional factors may rise resulting from complex overbank flow characteristics, which are not fully understood. In overbank flow, O'Sullivan observed that sediment transport rate in the inbank flow increases with the flow depth and reaches a maximum at the bankful depth and suddenly drops when the flow starts to inundate the floodplain [9]. Rameshwaran et al., Shiono et al. and Chan reported that a significant reduction of sediment transport rate occurs in the shallow overbank flow [10][11][12]. They explained that such reduction is caused by the increased in flow resistance induced by complex bedforms and momentum exchanges.

It is common knowledge that the present of vegetation in channel or floodplain will affect flow resistance, sediment transport and bedforms caused by scour and erosion processes. Vegetation will certainly reinforce and strength the soil surfaces through the development of root systems. The effective soil boundary is then more resistant to soil movement and erosion. Vegetation can also be impede the movement of the contact portion of the bed load and prevent or stabilise bedforms [13]. It is natural to grow vegetation next to a continuous source of water, namely growing trees and shrubs along riverbanks or floodplain edges. To date, research on studying the effect of vegetation along the floodplain edges in meandering compound channel on flow and sediment transport has not been undertaken yet. Loughborough University has been carried out experimental studies to understand an effect of vegetation along the main channel banks of compound meandering channel on stage discharge curve and sediment transport rate. In recent studies on flow mechanisms in compound meandering channels, there is a significant interaction between the floodplain flow and main channel flow in the cross-over section which generates extremely high flow resistance. This paper therefore focuses flow resistance and sediment transport rate in case of vegetation placed along the cross-over section to show the effect of vegetation on stage discharge curve and sediment transport rate.

Experiments

The experiments pertaining to this study were performed in a recirculation flume measuring 13 m in length, 2.4 m wide and 0.3 m deep with a fixed longitudinal gradient of 1/500. Fig. 1 shows a plan of the main features of the flume. Flow circulation is facilitated by two pumps recycling water from two storage namely sediment reservoir and main reservoir. The two pumps are capable to deliver a total discharge of around 30 litres per second. One pump carries the flow from the water reservoir back into the flume by a pipe installed along one side of the flume. A pump is calibrated in the laboratory before installation and capable of delivering the maximum discharge of about 23.2 litres per second. A special sediment pump is also used to convey a mixture of sediment and water from the sediment reservoir through a pipe system back to the inlet of the flume. The maximum pump capacity is around 6.8 litres per second and the flow is measured by a 3100 Maxflo flow meter which is calibrated by the manufacturer. The minimum flow rate used to ensure sediment smooth recirculation is 2.0 l/s. The water surface slope and flow depth in the flume are controlled by three tailgates with hand held adjustment at the end of the flume. This permits control of working uniform flow. The flume includes a meandering channel and floodplain. The floodplain is formed from 150 mm thick Styrofoam and finishing with the artificial grass. The main channel cross-section on the meandering channel is rectangular. The rectangular main channel has a base width of 0.4 m, a depth of 0.04 m. The main channel planform comprises three and half identical meander wavelengths over a total length of 11.9 m. Each meander bend consists of 120º circular arc with a centre radius of curvature of 0.765 m and successive bends are connected with 0.75 m cross-over length straight sections. The resulting sinuosity (the ratio of the distance along the channel between corresponding points on successive bends to the straight-line distance between these points) is 1.384.

The experimental investigation was carried out using rectangular blocks, one of which is with dimension of 0.06 m wide, 0.06 m long and 0.1 m height, to simulate roughness caused by vegetation. The aims of adopting the blocks were to examine the influence of vegetation on sediment transport behaviour and the change of flow mechanisms in the main channel during overbank flow. Although this may not represent the true scenario such shape and scale to the real situation, it was generally hoped that the block roughness and arrangement would create a logical step forward to model such flow. The measurements were carried out with four main arrangements of blocks at the edge of main channel/floodplain as shown in Fig. 2 with different densities. The blocks were placed in line with the meandering channel. Removing the number of block by every 5º created the different densities. The higher density had one block at every 5º, 10º for a middle density and followed by the lowest density for every 20º for meander bend, which consisted of a 120º circular arc. The different densities at the cross-over length are continued with similar spacing with different densities considered for a meander bend.

The main channel was filled with uniform sand with a mean size diameter of 0.855 mm. The depth of screeded sand bed was 40 mm below bankful level, which gives an aspect ratio of 10. This geometry was appropriate to investigate sediment transport and flow characteristics at higher flows. Furthermore, this aspect ratio is more realistic because the aspect ratio is within the range 10 to 15 that is commonly found in natural rivers (Sellin et al.) [14].

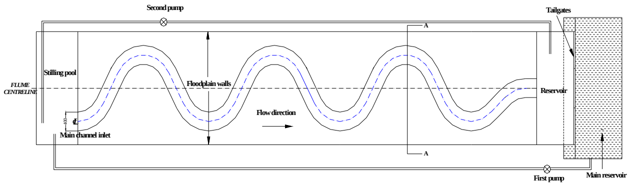

Fig. 1: Experimental flume plan

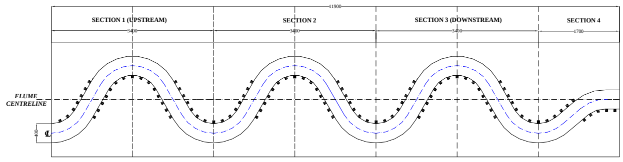

Fig. 2: *Case C* and *Case G* are the rectangular main channel cross-sections for fixed and mobile bed channels respectively.

Stage-discharge curves

The stage-discharge curves of various block density cases for the fixed and mobile beds are shown in Figs. 3 and 4. Fig. 3 shows the relationship between discharge (Q) versus water depth (H) for the fixed bed case. It is clearly seen from this figure that the water depth steadily increases with an increase in discharge in all the cases, including no block case, however the water depth is higher in the block cases than in no bock case. The difference in water depth between the no block and block cases increases as the discharge increases, however for different block density cases, it is surprisingly that all the stage-discharge curves show a very little difference, as a result, the variation of block density is insignificant in these cases. It is also clearly noticed that, at low overbank flow, the stage-discharge curves between all the cases are crossing each other at a discharge of around 0.0085 m^3/s and at flow depth = 60 mm. The below this depth, the denser the blocks, the lesser the discharge. The reason behind this is less momentum transfer from the floodplain to the main channel owing to continuous blocks along the cross-over section compared to that for no block case.

Fig. 4 shows the stage-discharge curves of various block densities for mobile bed cases. It can be noticed from the figure that there are three distinct regions of the stage discharge curves: for $Q < 0.01$ m^3/s in which all stage discharge curves are more or less same, for $0.01 m^3/s < Q < 0.017\ m^3/s$ in which the water depth of the 208 block case starts diverging from the other cases, and for $Q > 0.017$ m^3/s at which the water depths of both 54 and 107 block cases start diverging from the no block case.

For the fixed bed case, the stage discharge curves in all the block cases are similar. With this in mind, the a change of stage discharge curve is caused by bedforms that is only difference between the mobile and fixed bed cases in terms of geometrical feature of the channel. The results therefore suggest that bedforms start affecting the flow at the discharges of 0.01 m^3/s and 0.017 m^3/s for 208 blocks and both 54 and 107 blocks respectively. It is surprisingly that both stage discharge curves of 54 and 107 blocks are nearly same, which implies that bedforms of both cases are almost same. However, the water depths for both cases are higher than no block case after around Q = 0.014 m^3/s and lower than the 208 block case. When discharge is smaller than Q = 0.014 m^3/s, the H-Q curves for the 54 and 107 block cases and the fixed bed case are almost same, therefore this suggests no significant changes of bedforms from fixed bed.

Fig. 5 also shows the comparison of the stage-discharge curves between the fixed and mobile beds for no block and 208 blocks. The figure shows that the stage discharge curves of the fixed and mobile beds for no block are more or less parallel except at its beginning and end. The difference between both cases in terms of geometrical feature is bed forms. In this discharge range, it appears that the change of flow resistance caused by bedforms is at the same rate even the discharge changes. Looking at the stage discharge curves of no block and 208 blocks for the fixed bed, the difference in water depth increases as discharge increases after Q = 0.013 m^3/s. The only difference between both cases is blocks along the cross-over section. Blocks induce drag forces which normally increases as water depth increases. Therefore the difference between them is caused by the drag force due to blocks. It can be compared that the magnitude of flow resistances due to the bedforms and drag force by looking at the H-Q curves of no block with mobile bed and 208 blocks with fixed bed. There is a crossing point at 0.023 m^3/s where both flow resistances are same, and before this point bedforms contributes more than drag force and vis-à-vis after this.

In case of the mobile bed with no block and 208 blocks, the difference in water depth between them is much larger than that in the fixed bed case when the discharge is large. Similarly, the 208 block cases for the mobile and fixed beds also show large difference between them. The common factor for such large differences is bedforms. This suggests that the bedforms are significantly changed from those of no block case. It is possible to generate complex features of bedforms due to block wakes or interaction between the wake and main channel flow. When water depth is large, the blocks generate strong wakes which interact with the main channel flow and then create a number of secondary flows, consequently a series of craters behind the blocks in the main channel (i.e. bedforms behind bridge piers). Such bedforms increase flow resistance substantially, hence such large difference.

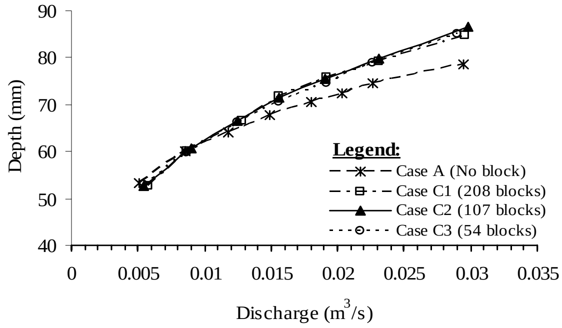

Fig. 3: Stage-discharge curves of different block densities for fixed bed

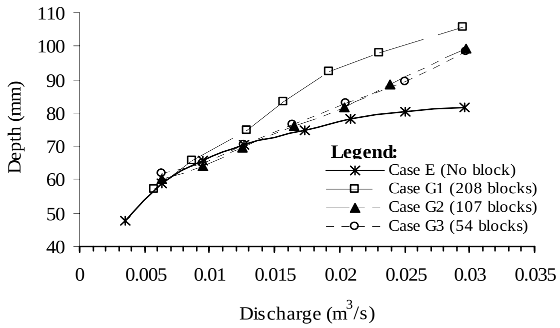

Fig. 4: Stage-discharge curves of different block densities for mobile bed

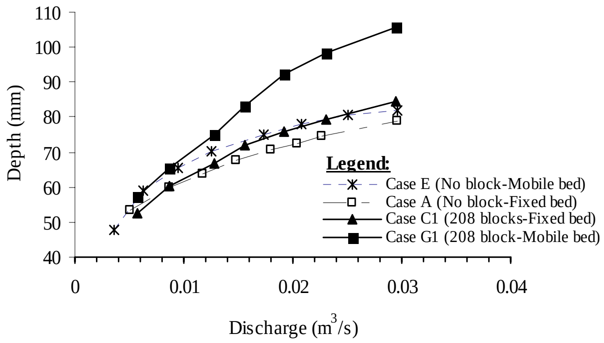

Fig. 5: Stage-discharge relationships between fixed bed and mobile bed cases

Manning Coefficient

The Manning coefficient normally represents flow resistance in open channel. The single channel Manning's n was calculated for each overbank discharge using equation (1) below. The variation of the single channel Manning's n with the relative water depth (Dr = floodplain water depth / main channel water depth) is shown in Fig. 6.

$$n = \frac{AR^{2/3} S_o^{1/2}}{Q} \qquad (1)$$

where R is the hydraulic radius, A is the cross sectional area and S_o is the channel slope.

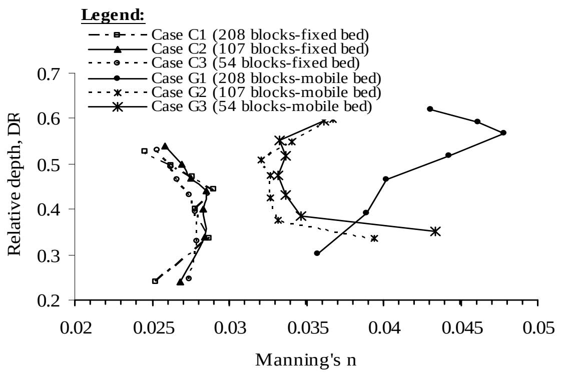

Fig. 6: Manning's n of different block densities for fixed bed and mobile bed

Fig. 6 shows the Manning's n varying between 0.025 and 0.0285 for the fixed bed in which there exist three regions: n increases to Dr = 0.35, remains relatively constant till Dr = 0.45 and then starts to decreases. For mobile bed, n varies more than that in the fixed bed case and the values are higher n ranges from 0.0315 to 0.049, which is 30% larger than the fixed bed case. This suggests that bedforms give such magnitude contributing the total flow resistance. The 208 block case shows totally different behaviour from the others and the values are significantly larger as the relative water depth increases. This implies that bedforms change drastically. In the 54 and 107 block cases there are also three regions of the Manning's n behaviour: decreasing to Dr = 0.37, remaining a constant to Dr = 0.5 and then increasing. However in the 208 block case, the Manning's n increases from the bankful to Dr = 0.55 and then decreases.

Sediment Transport Rate

Fig. 7 shows the sediment transport rate with the discharge for the mobile bed channel. Sediment transport rates for all the cases behave a very similar trend in such way that it starts to decrease to minimum then increase. Looking at sediment transport rates for all the block cases, it is also noticed that as block density increases, the range of discharge that the sediment transport rates remain minimum becomes narrower. The sediment transport rate is directly related with velocity in the main channel and therefore the reduction of sediment transport rate means the reduction of velocity.

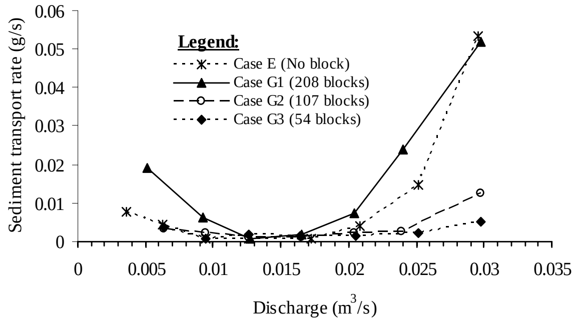

Fig. 7: Discharge and sediment transport relationship for mobile bed channel cases

Rameshwaran et al. gave the reason for the decrease in the sediment transport rate in compound meandering channel [10]. Relative slow floodplain flow, compared with the meandering channel flow, enters the main channel in the cross-over section, which reduces velocity in the main channel by momentum transfer due to interfacial turbulence at the bankful level. This interfacial turbulence also interacts with bed and develops irregular bedforms, which has been observed [11], meaning an increase in flow resistance in the main channel, as a result, a substantial reduction of velocity in the main channel occurs, hence reduction of sediment transport rate.

With this in mind, the reason why the range of discharge for minimum sediment transport rate becomes smaller as the block density increases will be explained below. When block density increases, the gaps between blocks is getting narrower and narrower, meaning that flow through the gaps from floodplain becomes lesser and lesser, hence lesser and lesser interaction between the floodplain and main channel flows in the cross-over section, as a result, the velocity in the main channel in higher density block case does not decrease as much as that for lesser density block case. In addition, the velocity just outside of the blocks also becomes faster in the higher density block case at the same flow since flow becomes smaller in the blocked area, and consequently the velocity becomes faster quickly around the bend apex. Thus the overall main channel flow becomes faster as block density increases. Therefore as flow rate increases, velocity in the main channel increases hence sediment transport rate quickly increases.

From stage-discharge curves, it is not easy to understand such sediment transport behaviour. This result demonstrates how the block density along the cross-over section in compound meandering channel influences overall flow resistance and sediment transport rate.

Conclusions

Experiments were carried out in compound meandering channels with vegetation along the floodplain edges to investigate the effect of vegetation on stage-discharge curve and sediment transport rate in the fixed and mobile meandering channels. The main findings are as follows. In the fixed bed case, stage-discharge curves were almost same even different block densities, whereas in the mobile case, they are quite different from those in the fixed bed case. When the blocks are the densest the water depth is higher than the other two cases, but both other cases are nearly same water depth as with the fixed bed case. The Manning coefficient used as flow resistance is considerably higher in the mobile case than the fixed case, i.e. bedforms give 30% or more contribution to the total flow resistance. The sediment transport rate in the main channel starts to decrease as soon as flow becomes overbank, remains its minimum until water depth becomes floodplain flow faster enough to accelerate the main channel flow. As block density increases, the range of discharge that maintains the sediment transport rate at its minimum becomes narrower. This paper shows how vegetation density along the floodplain edges affects overall flow resistance and sediment transport rate in the meandering channels for overbank flow.

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