BEDFORMS AND SEDIMENT TRANSPORT RATES IN MEANDERING CHANNEL INFLUENCED BY FLOODPLAIN ROUGHNESS

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The aim of this paper is to improve an understanding of physical processes involved in sediment transport mechanisms and bedform evolution in a two stage meandering channel. In this study, a laboratory flume was used since it is difficult to observe bedforms and to obtain sediment transport rates in natural rivers during flood. A series of experiments were conducted to measure stage-discharge data, sediment transport rates, and bedforms in a meandering channel with different roughened floodplains for overbank flows. Detailed measurements have shown that the bedforms considerably vary with different water depths and floodplain roughness. The sediment transport rate increases while the flow is inbank, and once the flow is overbank, it starts decreasing till at a certain water depth and then increasing again. The bedforms have ripples and dunes at a water depth when a minimum sediment transport rate occurs. The water depth at the minimum sediment transport rate also varies due to floodplain roughness.

Key words: *Bedforms, meandering channel, overbank flows, floodplain roughness, sediment transport rate*

1. INTRODUCTION

Many studies on compound meandering mobile channels with smooth and rough floodplains have been carried out using a relatively larger flume, UK-Flood Channel Facility (FCF), HR Wallingford and small university channels.[1),2),3),4)] The flow structures found from those studies are more complex than those found in compound straight channels. Such complex flow structures are mainly caused by floodplain flow entering the main channel with an angle. Slower or faster floodplain flow relative to the main channel flow interacts with the main channel flow and bedform during flood. An entering angle and magnitude of floodplain flow to the main channel is directly related to sinuosity and floodplain roughness which are important to determine flow resistance and sediment transport rate in the main channel. They Lyness *et al*[2)] and O'Sullivan[3)] investigated the effect of a main channel sinuosity on flow resistance, and found that the flow resistance in the main channel increases as the sinuosity increases, in particular, at low overbank flow depths, flow resistance increases significantly. Shiono and Muto[5)] analysed the interfacial turbulence on the horizontal plane at the bankfull level using turbulence data, and found the higher the sinuosity the larger the turbulence, which means more intensive momentum exchange. Thus, at a high sinuous channel, the flow in the main channel slows down. Shiono *et al*[6)] also reported that flow resistance increases owing to the bedform change and the momentum exchange between the main channel and floodplain flows. The magnitude of momentum exchange depends on the magnitude of floodplain velocity entering the main channel hence it is dependent on floodplain roughness. Floodplain roughness will therefore play an important role in determining momentum exchange at the bankfull level. To date, there are few studies on floodplain roughness associated with flow resistance, but not with bed forms and sediment transport rates. This paper demonstrates the effect of floodplain roughness on sediment transport rates and bedforms in a meandering channel for overbank flows.

2. EXPERIMENTS

The dimensions of a flume used in this experiment were 13m long, 2.4m wide and 0.3m deep with a fixed longitudinal gradient of 1/500 (Table 1). Flow circulation was facilitated by three pumps. Three pumps were used to deliver a total flow rate up to 79 l/s. One of which was to convey a mixture of all sediments and water through recirculation pipe

Table 1 Channel configuration

Meander length (m)	Total width (flume width) (m)	Meander belt width (m)	Main channel width (m)	Cross over length (m)
3.4	2.4	1.815	0.4	0.75
Side slope (o)	**Radius of curvature (m)**	**Sinuosity**	**Valley slope**	
90	0.765	1.3837	1/500	

Table 2 Experiments

Series name	Main channel Aspect ratio	Bed mobility	Roughness element	Sediment size d_{50}(mm)
G1	5.33	Mobile	Smooth	0.855
G2	10.	Mobile	Smooth	0.855
G3	5.33	Mobile	Smooth	0.855
G4	10.	Fixed	Smooth	
G5	10.	Mobile	Grass	0.855
G6	10.	Fixed	Grass	
G7	10.	Mobile	Grass+blocks	0.855

system to the inlet of the meandering channel. The sediment was collected at the inlet. The minimum flow rate used to ensure sediment re-circulation is 1.9 l/s.

The flume incorporated 3¼ meander units with a wavelength of 3.4m and a sinuosity of 1.38. The channel geometry parameters of the experimental flume are summarized in Table 1. The channel was formed from 150mm thick Styrofoam floodplain sections, which were cut into shape and glued onto the flume basin. Paint was applied to ensure a homogeneous smooth surface roughness. The radius of curvature is defined from the channel centre. The cross-over section is the straight section between arc sections.

The test section was located at the second meander unit from the inlet, which was constructed by transparent Perspex in order to ease flow visualization in the channel. The sinuous main channel has a constant top width of 0.4m and bank slopes of 90^{o}. The mobile bed channel was formed by uniform sand and the bedform was allowed to develop naturally in the channel. The main channel was filled with uniform sand with a mean size of

Fig. 1 Pictures of floodplain roughness for G2, G5 & G7 cases

0.855mm. At the first experiment (G1), the depth of screeded sand bed was 75mm below bankful level, which gives an aspect ratio of 5.33 in the main channel (Table 2). For higher flow cases, the sediments on some part of the bed were washed away by the flow and flume bed was exposed. As a result, this geometry was inadequate to investigate sediment transport and flow characteristics at higher flows. It was then decided to alter the depth of the screeded sand bed to 40mm, which gives an aspect ratio of 10.

The flume was run at bankfull depth for 36 hours to establish bed form, after which the flow was incrementally increased for overbank depths. At each of the increments, water ran for 36 hours before the measurements.

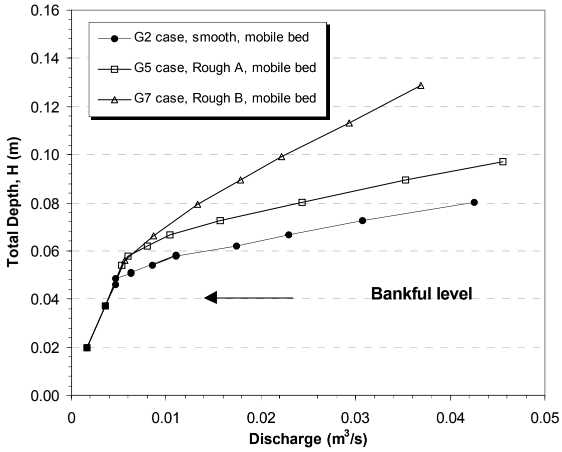

Fig. 2 Stage discharge curves

For each experiment, the floodplain was roughened with a different roughness element (see Fig. 1). The first experiment was a 'smooth' floodplain, which was made of Styrofoam. For the second experiment, the floodplain was roughened by gluing a layer of 8mm thick of artificial grass (Golf Putting Grass) on Styrofoam surface. For the third experiment, a combination of the artificial grass and rectangular concrete blocks was used.

All rectangular blocks had an identical dimension (6.2x 6.2cm), and were laid in a square array with an additional block in the centre, which make a rhomboidal pattern having a spacing of 0.4 x 0.4m. These blocks were placed on the floodplain intended to simulate high roughness.

3. STAGE-DISCHARGE

Stage-discharge data were collected over five experiments that incorporated flat and mobile beds with various roughened floodplains (experiment numbers G1, G2, G4, G5, and G7). The details of each experiment are tabulated in Table 2. In this paper, three experiments for mobile bed cases were used. The stage discharge data for G2 G5 and G7 are shown in Fig. 2. It is apparent from this figure that the discharge increases almost linearly with stage for inbank flow. It also appears that there is a discontinuity on the stage-discharge curves at the beginning of the overbank flow for all experiments. The reason for the discontinuity is due to slower floodplain flow entering the main channel. This retards a faster main channel flow when the floodplain starts to be inundated. After the flow depth reaches at a certain depth the stage-discharge relationship becomes nearly linear again.

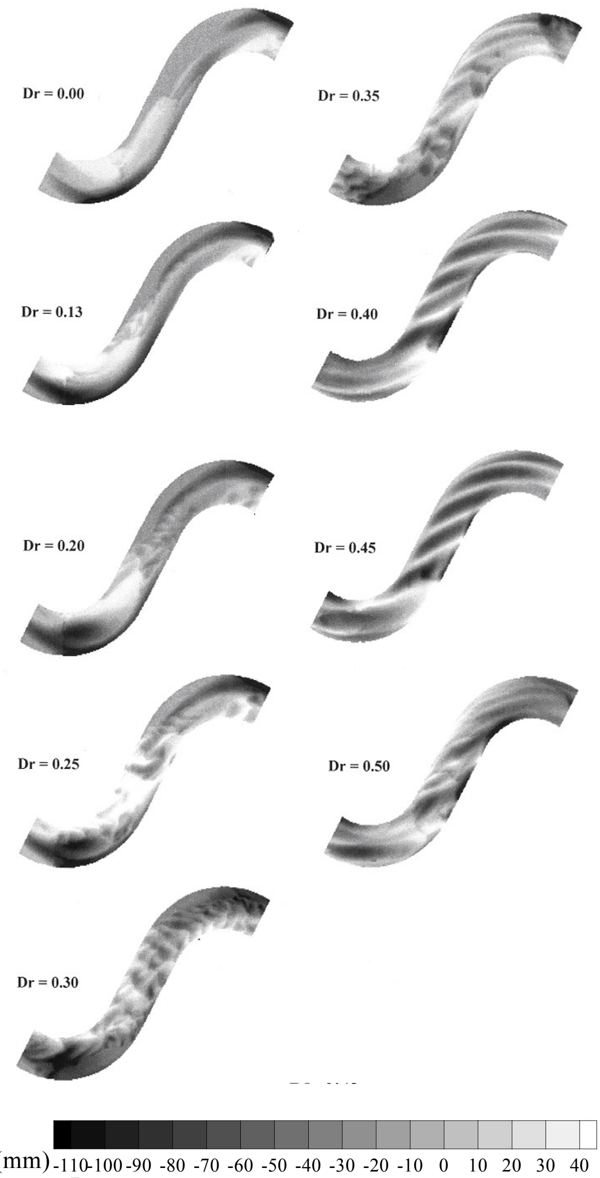

Fig. 3 G2 bedforms for various over bank flows
(The zero is initial bed level, i.e. 40mm below the floodplain.)

As for the influence of floodplain roughness to overall discharge, the figure indicates that the smooth floodplain case (i.e. G2) had a greater efficiency to convey water when compared to the roughened floodplain cases (i.e. G5 & G7). For instance, the smooth floodplain case conveys up to 50% more than the roughened floodplain cases at a total depth of 0.08m, and the conveyance efficiency was worse at higher flow stages for the roughened floodplain cases. In the block roughened floodplain case (i.e. G7), it is apparent that the stage-discharge curve increases linearly after the water depth greater than 0.07m. From comparison between the roughened floodplain cases, it appears that the rate of divergence between the grass and block

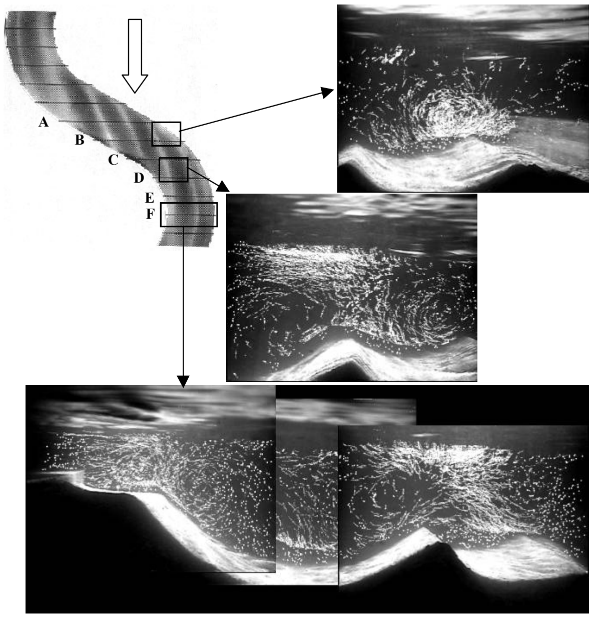

Fig. 4 Secondary flow structure along the ridges at Dr=0.45

floodplains is significant, however, the stage-discharge gradients between the smooth and grass floodplains are very similar. This implies that the flow resistance due to form drag of the blocks on the floodplain has a great effect on the overall conveyance. Under the block case, the floodplain roughness is the dominant factor attributed to the overall discharge conveyance.

4. BEDOFRMS

Bedforms were recorded by a digital Photogrammetry technique, and digital elevation model (DEM) images were generated using IMAGINE software. In order to show distinctive features of bedform, the DEM images were generated in grey-scale; darker colour indicates deeper part of the channel, and lighter colour indicates shallower. The water is flowing from left to right in Figs. 3, 5 & 6.

Fig. 3 shows a series of bed topographies for the smooth floodplain G2 case. The bedform at the bankfull stage (Dr=0.0) exhibits a typical bedform profile as normally expected for inbank flow. The deepest part appears near the outer bank with a point sand bar formed from the inner bank from the apex section to the centre at the cross-over section.

At Dr=0.25, the bedform starts to deviate from the typical bankfull pattern to irregular bedforms. At Dr=0.30, dunes and ripples were formed in the crossover reach. They are irregular in shape with having 10-30mm amplitudes. The dune and ripples

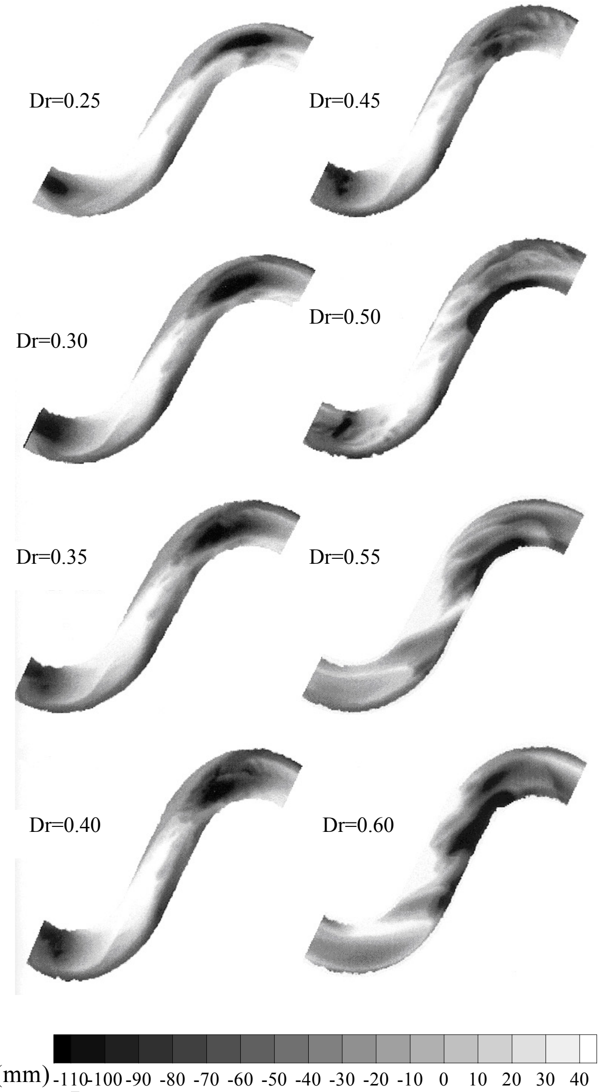

Fig 5. G5 bedforms for various overbank flows
(The zero is initial bed level, i.e. 40mm below the floodplain.)

disappears at depth ratio Dr=0.35 and irregular sandbars are formed. At Dr=0.45, very distinctive regular sand bars with a series of ridges are formed. The directions of the ridges are not in line with either the valley direction or the meandering channel directions. In order to associate these ridges with flow, flow visualisation was carried out. Fig. 4 shows the results of the visualisation experiment[7)], which shows an existence of a number of strong secondary flow cells over the ridges of the bedforms. It can be seen from Fig. 4 that secondary flow is generated at the edge of floodplain in the main channel and is developed and decayed along the ridge. There also appears a counter direction of the secondary flow circulation that occurs near the ridge. These secondary flows keep the ridge in form.

After Dr=0.50, the wavy bedforms disappear and the channel bed becomes relatively plane. The diminishing of the bedforms inevitably reduces the

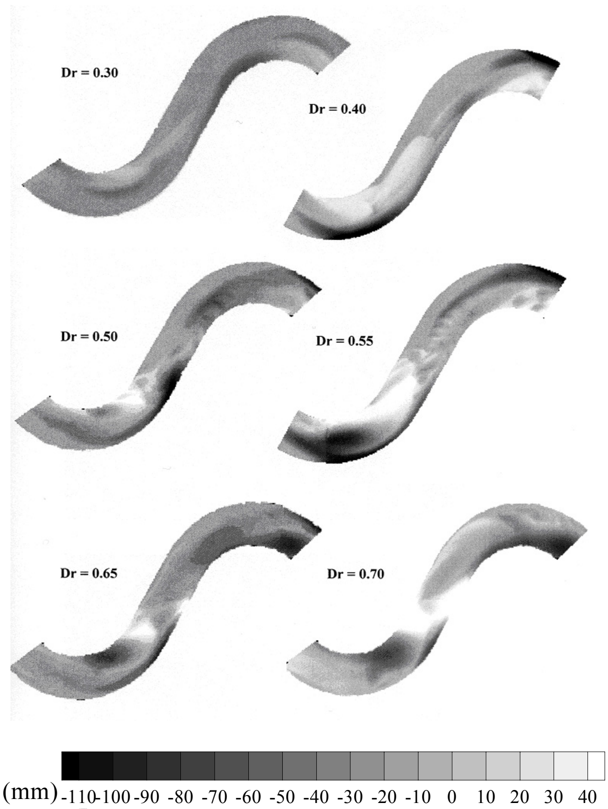

Fig. 6 G7 bedforms for various overbank flows
(The zero is initial bed level, i.e. 40mm below the floodplain.)

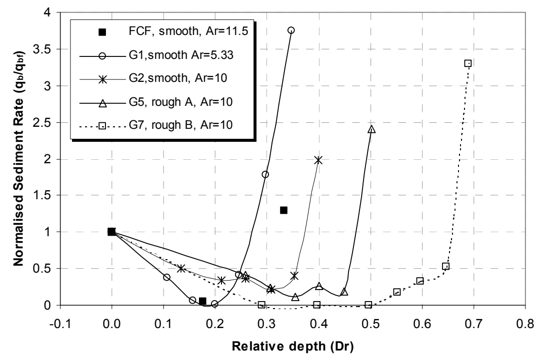

Fig. 7 Sediment transport rates of different floodplain roughnesses

effect of form friction on the overall friction in the channel.

Fig.s 5 and 6 show an aerial view of bed topographies for the roughened floodplain G5 and G7 cases respectively. From these figures, it is apparent that the bedforms in the channel significantly differ from those in the smooth floodplain case (G2). The bed features in the roughened floodplain cases have much more irregular and variable patterns.

In case G5, as shown in Fig. 5, there are two pools which are observed as the deeper regions located at the downstream bend apex from Dr=0.25 to Dr=0.4. On the other hand a shallower depth occurs in the inner region just after bend shown as the white colour. There is not much change in the bed topography up to Dr=0.40. At Dr=0.45, a number of ripples are formed at the downstream apex section. At Dr=0.55, the ripples disappear leaving a relatively large scouring region at the outer bank immediately after the crossover section and regular ridges are formed. The regular ridges gradually disappear at Dr=0.60.

For case G7, as shown in Fig. 6, the bedform at Dr=0.30 is fairly similar to that at the bankful stage. The length of a point sand bar is elongated at Dr=0.4 but the fundamental shape of bedform remains the same till Dr=0.50. At Dr=0.55, the bedform becomes irregular, constituting of dunes and ripples along the cross over section. It was observed during the experiment that sediment was carried away from the main channel and deposited onto the floodplain due to the strong "cross flow". The transported sediment on the floodplain re-enters the main channel in next cross-over section and subsequently causes deposition in the main channel. At Dr=0.65, the dunes and ripples disappear. The amount of sediment load migrating along the floodplain in the valley direction increased. This deposited sediment moving along the floodplain contributes to an increase in floodplain flow resistance and also a reduction in channel depth particularly at the crossover section in the main channel as seen at Dr=0.7.

5. SEDIMENT TRANSPORT RATES

The visualization of the sediment movement was carried out by an underwater video camera, and confirmed that none of the sediment was transported in suspension mode for all tested cases. The sediment transport rate is therefore discussed in terms of bed load as this is the only transport mode observed during the experiments.

The sediment was collected in 15 - 30 minute intervals over a period of 6 hours. The transport rate was calculated by dividing the dry sediment weight by the time interval. The mean transport rate was calculated by taking an average of the transport rates over the whole collection period.

For the purpose of rendering suitable data for comparison, each transport rate (q_b) was normalised by the transport rate at bankfull level (q_{bf}). The normalised sediment transport rates with relative depths for all series of the experiments together with the FCF data are presented in Fig. 7. It can be seen from the figure that the sediment transport rate decreases till the relative water depth Dr=0.20 for G1, Dr=0.35 for G2, Dr=0.45 for G5 and Dr=0.5 for G7. This means that the bounds of water depth for the decrease in sediment transport rate extend to a higher depth as the floodplain roughness increases. The reason for this is that as floodplain roughness increases, floodplain velocity becomes smaller than the main channel velocity in wider bounds of water depth and when this smaller velocity enters the main channel, the momentum exchange takes place between slower floodplain and faster main channel flows, as a result, the main channel velocity becomes slower.

Furthermore from the DEMs images of beforms illustrated in the previous section, the DEM images show a great variation of bedforms as water depth changes. From Figs. 3, 5 and 6, ripples and dunes distinctly appear in the cross-over section when the sediment transport rate is minimum. Wu and Wang[8)] reported that the resistance to flow due to this type of bed form could be more than 10 times that of the grain friction. Hence bedforms also play an important role in the reduction of the main channel velocity and sediment transport rate.

This clearly shows that floodplain roughness affects flow resistance, bedform and sediment transport rate in the main channel during flood.

6. CONCLUSIONS

The experimental results show that the smooth floodplain case has a greater efficiency to convey water when compared to the roughened floodplain channel cases. The conveyance efficiency in the smooth floodplain case is up to 50% more than in the grass roughened floodplain case and the efficiency is worsen as flow stage increases in the block roughened floodplain case because of an increase in drag force due to the blocks.

It was observed that bedform changes four phases that occur during flood; 1) A typical inbank bed form kept till an impact of floodplain flow occurs in the main channel, 2) ripples and dunes formed as floodplain velocity increases, 3) relatively regular sand bars caused by secondary flows and 4) sand bars and irregular bedforms disappeared. These patterns remain similar even floodplain roughness is changed, however they occur at different relative depths.

In most tested cases, sediment transport rate decreases during flooding and increase again after at which a minimum sediment transport rate occurs. This minimum sediment transport rate occurs at a water depth when ripples and small amplitude of dunes appear on the bed. The water depth at a minimum sediment transport rate extends higher as the floodplain roughness increases.

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