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ROUGHNESS CHARACTERISTICS IN TWO STAGE MEANDERING AND STRAIGHT COMPOUND CHANNELS

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ABSTRACT

During uniform flow in open channels the resistance to the flow is dependant on a number of flow and channel parameters. The usual practice in one dimensional analysis is to select a value of n depending on the channel surface roughness and take it as uniform for the entire surface for all depths of flow. The influences of all the parameters are assumed to be lumped into a single value of n. Patra (1999), Patra and Kar (2000), and Pang (1998) have shown that Manning's coefficient n not only denotes the roughness characteristics of a channel but also the energy loss in the flow. The larger the value of n, the higher is the loss of energy within the flow. Although much research has been done on Manning's n, for straight channels, very little has been done concerning the roughness values for simple meandering channels and also for meandering channels with floodplains. An investigation concerning the loss of energy of flows with depths ranging from in bank to the over bank flow, spreading the water to floodplains for meandering and straight compound channels are presented. The loss of energy in terms of Manning's n, Chezy's C, and Darcy-Weisbatch coefficient f are evaluated.

INTRODUCTION

Experimental results are presented concerning stage-discharge relationships and resistance for compound channels with a rigid main channel bed and rigid smooth floodplains. The variation of resistance with depth, and the abrupt reduction in resistance at the bankfull stage, are all linked to the stage-discharge relationships. Distribution of roughness coefficients in a compound channel section is an important aspect that needs to be addressed properly. Water that flows in a natural channel is a real fluid for which the action of viscosity and other forces cannot be ignored completely. Owing to the viscosity, the flow in a channel consumes more energy. Usually Chezy's, Manning's or Darcy-Weisbach equation is used to calculate the velocity of flow in an open channel. The roughness coefficient in these cases is represented as c, n and f respectively. Due to its popularity, the field engineers mostly use Manning's equation to estimate the velocity and discharge in an open channel. While using Manning's equation, the selection of a suitable value of n is the single most important parameter for the proper estimation of velocity in an open channel. Major factors affecting Manning's roughness coefficient are the (i) surface roughness, (ii) vegetation, (iii) channel irregularity, (iv) channel alignment, (v) silting and scouring, (vi) shape and the size of a channel, and (vii) stage-discharge relationship. However, in one dimensional analysis, it is difficult to model the influence of all these parameters individually to formulate a simple equation for the estimation of velocity and discharge rate in an open channel under uniform flow conditions. Pang (1998) and Patra (1999) have shown that Manning's coefficient n not only denotes the roughness characteristics of a channel but also the energy loss of the flow. The influences of all the forces that resist the flow in an open channel are assumed to have been lumped to a single coefficient n.

Due to flow interaction between the main channel and floodplain, the flow in a compound section consumes more energy than a channel with simple section carrying the same flow and having the same type of channel surface. The energy loss is manifested in the form of variation of resistance coefficients of the channel with depth of flow. The variation of Manning's roughness coefficient n, Chezy's C and Darcy - Weisbach friction factor f with depths of flow ranging from in-bank channel to the over-bank flow are discussed. Flood plains of river basins are densely vegetated. The values of n are determined from the factors that influence the roughness of a channel and flood plain. In densely vegetated flood plains, the major roughness is caused by trees, vines, and brush. The n value for this type of flood plain can be determined by measuring the vegetation density of the flood plain.

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Photographs of flood-plain segments where n values have been verified can be used as a comparison standard to aid in assigning n values to similar floodplains. The results of Manning's formula, an indirect computation of stream flow, have applications in floodplain management, in flood insurance studies, and in the design of bridges and highways across flood plains. Manning's formula is written as

$$V = \frac{1}{n} R^{2/3} S_e^{1/2} \quad (1)$$

where V = mean velocity of flow, in meters per second, R = hydraulic radius, in meters, Se = slope of energy grade line, in meters per meter. n = Manning's roughness coefficient.

It would be impractical in this guide to record all that is known about the selection of the Manning's roughness coefficient, but many textbooks and technique manuals contain discussions of the factors involved in the selection. Three publications that augment this guide are Barnes (1967), Chow (1959), and Ree (1954). Although much research has been done to determine roughness coefficients for open-channel flow (Carter and others, 1963), less has been done to study the variation of n with flow depth for the same channel, more so when the channel flows overtop the banks. The roughness coefficients for these channels are typically very different from those for in bank flows. There is a tendency to regard the selection of roughness coefficients as either an arbitrary or an intuitive process. Specific procedures can be used to determine the values for roughness coefficients in channels and flood plains. The n values for channels are determined by evaluating the effects of certain roughness factors in the channels. Values of the roughness coefficient, n may be assigned for conditions that exist at the time of a specific flow event, for average conditions over a range in stage, or for anticipated conditions at the time of a future event. The discussion made in this paper is limited to show the variation of the channel roughness coefficient for application to one-dimensional open-channel flow problems.

Meandering is a degree of adjustment of water and sediment laden river with its size, shape, and slope such that a flatter channel can exists in a steeper valley. During floods, part of the discharge of a river is carried by the main channel and the rest are carried by the floodplains located to its sides. Once a river stage overtops its banks, the cross sectional geometry of flow undergoes a steep change. The channel section becomes compound and the flow structure for such section is characterized by large shear layers generated by the difference of velocity between the main channel and the floodplain flow. Due to different hydraulic conditions prevailing in the river and floodplain, mean velocity in the main channel and in the floodplain are different. Therefore flood estimation of natural channels cannot be correct unless we incorporate a procedure to obtain the correct values of n or c for the main channel and floodplains. The usual procedure in such a compound channel using one dimensional flow analysis is to separate the compound channel into sections using a vertical, horizontal or a diagonal interface plane. Since the hydraulic parameters affecting the main channel and floodplains of a compound section are different, there is a marked difference in the values of coefficient n from in bank to over bank flow. Moreover, when the compound channel is used as single section, the value of n again becomes different. This paper also discusses the variation of n using a section as single channel and also using it as sum of more than one subsection.

EXPERIMENTAL SETUP

Experimental data from three types of channels from IIT Kharagpur With the channel of NIT Rourkela are presented in this paper. Plan forms of the three types of meandering experimental channels with floodplains are shown in Fig.1. The summery of experiments conducted are given in Table 1. The experimental results concerning the Manning's n, Chezy's C and Darcy - Weisbach friction factor f for simple meander channels (in-bank flow) for all the three types are given in Table.2, where as for meander channels with floodplains (over-bank flow) the corresponding results are given in Table. 3. In Type-I, series-I channel, the flow is confined to in-bank only, whereas data for the over-bank flow for the same channel is given in series-II of Table 3. Type I channel is asymmetrical with two unequal floodplains attached to both sides of the main channel. Similarly Type-II and IIR channels are asymmetrical with only floodplain attached to one side of the main channel. All surfaces of the channel IIR are roughened with rubber beads of 4 mm diameter at 12 mm centre to centre. The in bank flow data of Type-II and IIR are given in series-III and V of Tables 2 and 3, while the over bank flow data are given in series IV and VI respectively in these tables. Type-III channel is symmetrical with two equal floodplains attached to both sides of the main channel. Like wise the details of in bank flow are given in series VII of Table 2 and the over bank flow are given in series VII of Table 3.

Details of the experimental setup and procedure concerning the flow and velocity observations in meandering channels with floodplains of Type-I, Type-II and IIR are reported earlier (Patra 1999; Patra and Kar, 2000; and Patra and Kar, 2004). These experiments are conducted at the Water Resources and Hydraulic Engineering Laboratory of the Civil Engineering Department of the Indian Institute of Technology, Kharagpur, India. For Type–IV, The experiments concerning the flow in simple meander channels and meander channel - floodplain geometry have been conducted at the Fluid Mechanics and Water Resources Engineering Laboratory of the Department Civil Engineering, National Institute of Technology, Rourkela, India. The centerline of the meandering channel is taken as sinusoidal. Inside a tilting flume a compound channel consisting of a meandering main channel with floodplain(s) is fabricated. The channel surfaces formed out of Perspex sheets represents smooth boundary. The channels are placed inside a rectangular tilting flume made out of metal frame and glass walls. The tilting flume has the overall dimension of 12 m long and 0.60 m wide for To facilitate fabrication, the whole channel length has been made in blocks of 1.20 m length. The flume is adequately supported on suitable masonry at its bottom. The geometrical parameters of the experimental channels are given in **Table I**

Water is supplied to the experimental channel from an overhead tank. An glass tube indicator with a scale arrangement in the overhead tank enables to draw water with constant flow head. The stilling tank located at the upstream of the channel has a baffle wall to reduce turbulence of the incoming water. An arrangement for the smooth transition of water from the stilling tank to the experimental channel is made. At the end of the experimental channel, water is allowed to flow over a tailgate and into a sump. From the sump water is pumped back to the overhead tank, thus setting a complete re-circulating system of water supply for the experimental channel. The tailgate helps to establish uniform flow in the channel.

The discharge is measured in two ways. The water flowing out of the exit end of the experimental channel is diverted to a rectangular measuring tank and the change in the depth of water with time is measured by a glass tube indicator system with a scale of accuracy 0.01cm

The ratio α between overall width B and main channel width b of the meandering compound channels could be varied from 2.13 to 5.25 for the three types of channels. The channel sections are made from Perspex sheets for which the roughness of floodplain and main channel were identical. The observations are made at the section of maximum curvatures (bend apex) of the meandering channel geometries

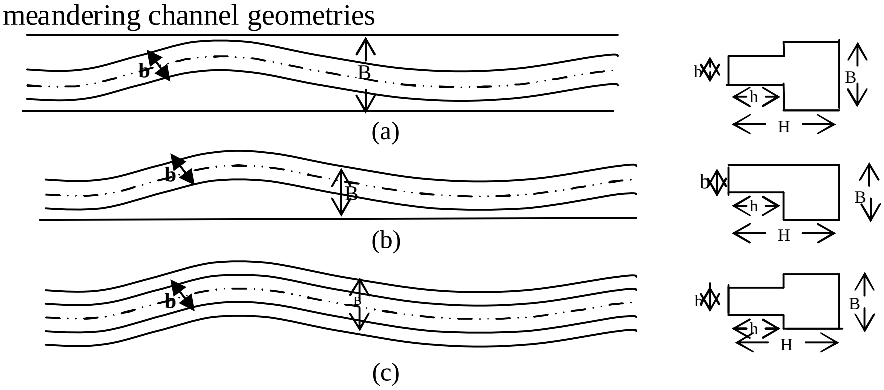
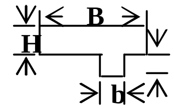
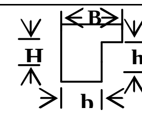
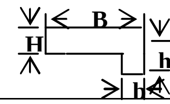
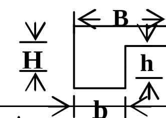
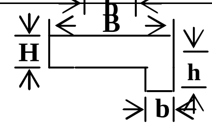
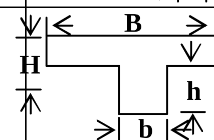
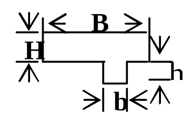


Fig. 1 Plan Forms of Meandering Experimental Channels with Floodplains

Table 1 Summary of Experimental Runs for Meandering Channel with Floodplains at Bend Apex

Experi-ment Type	Channel surface	Bed slope	Top width B(cm)	Main channel width b(cm)	Depth of lower main channel	$\alpha = B/b$	Sinuo-sity S_r	Shape of the compound channel section
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Type -I	smooth	0.0061	52.5	10	10	5.25	1.22	
	smooth	0.0061	52.5	10	10	5.25	1.22	
	smooth	0.0061	52.5	10	10	5.25	1.22	
Type –II	smooth	0.004	21.3	10	10	2.13	1.21	
	smooth	0.004	21.3	10	10	2.13	1.21	
	smooth	0.004	21.3	10	10	2.13	1.21	
Type -I I	smooth	0.004	41.8	10	10	4.18	1.21	
	smooth	0.004	41.8	10	10	4.18	1.21	
Type -I IR	rough	0.004	21.3	10	10	2.13	1.21	
	rough	0.004	21.3	10	10	2.13	1.21	
	rough	0.004	21.3	10	10	2.13	1.21	
Type -I IR	rough	0.004	41.8	10	10	4.18	1.21	
	rough	0.004	41.8	10	10	4.18	1.21	
	rough	0.004	41.8	10	10	4.18	1.21	
Type -I II	smooth	0.00278	138	44	25	3.136	1.043	
	smooth	0.00278	138	44	25	3.136	1.043	
	smooth	0.00278	138	44	25	3.136	1.043	
Type -IV	smooth	0.0078	57.7	12	12	4.808	1.44	
	smooth	0.0078	57.7	12	12	4.808	1.44	
	smooth	0.0078	57.7	12	12	4.808	1.44	

MANNING'S RESISTANCE FACTORS FOR VARIOUS CHANNEL SURFACES

Distribution of energy in a compound channel section is an important aspect that needs to be addressed properly. Water that flows in a natural channel is a real fluid for which the action of viscosity and other forces cannot be ignored completely. Owing to the viscosity, the flow in a channel consumes more energy. While using Manning's equation, the selection of a suitable value of n is the single most important parameter for the proper estimation of velocity in an open channel. Major factors affecting Manning's roughness coefficient are the (i) surface roughness, (ii) vegetation, (iii) channel irregularity, (iv) channel alignment, (v) silting and scouring, (vi) shape and the size of a channel, and (vii) stage-discharge relationship. Patra (1999), Patra and Kar (2000), Pang (1998), and Willets & Hardwick (1993) have shown that Manning's n not only denotes the roughness characteristics of a channel but also the energy loss in the flow. The influences of all the forces that resist the flow in an open channel are assumed to have been lumped to a single coefficient n.

Due to flow interaction between the main channel and floodplain, the flow in a compound section consumes more energy than a channel with simple section carrying the same flow and having the same type of channel surface. The energy loss is manifested in the form of variation of resistance coefficients of the channel with depth of flow. The variation of Manning's roughness coefficient n, Chezy's C and Darcy - Weisbach friction factor f with depths of flow ranging from in-bank channel to the over-bank flow are discussed. Floodplains of river basins are densely vegetated. The values of n are determined from the factors that influence the roughness of a channel and floodplain. In densely vegetated flood plains, the major roughness is caused by trees, vines, and brush. The n value for this type of floodplain can be determined by measuring the vegetation density of the floodplain.

Suggested values for Manning's n are tabulated in Chow (1959), and Henderson (1966). Roughness characteristics of natural channels are given by Barnes (1967).Though there are large numbers of formulae/procedures available to calculate Manning's n for a river reach, the following four methods are found to be more usefull.

1. Jarrett's (1984) equation for high gradient channels $n = \dfrac{0.32 S^{0.38}}{R^{0.16}}$ (5)

where S is the channel gradient, R the hydraulic radius in meters. The equation was developed for natural main channels having stable bed and bank materials (boulders) without bed rock. It is intended for channel gradients from 0.002 – 0.04 and hydraulic radii from 0.15 – 2.1m, although Jarrett noted that extrapolation to large flows should not be too much in error as long as the channel substrate remains fairly stable.

2. Limerions's (1970) equation for natural alluvial channels $n = \dfrac{0.0926 R^{0.17}}{1.16 + 2\log(R/d_{84})}$ (6)

where R is the hydraulic radius and d_{84} the size of the intermediate particles of diameter that equals or exceeds that of 84% of the streambed particles, with both variables in feet. This equation was developed for discharges from 6 – 430 m^3/s, and $n/R^{0.17}$ ratios up to 300 although it is reported that little change occurs over $R > 30$.

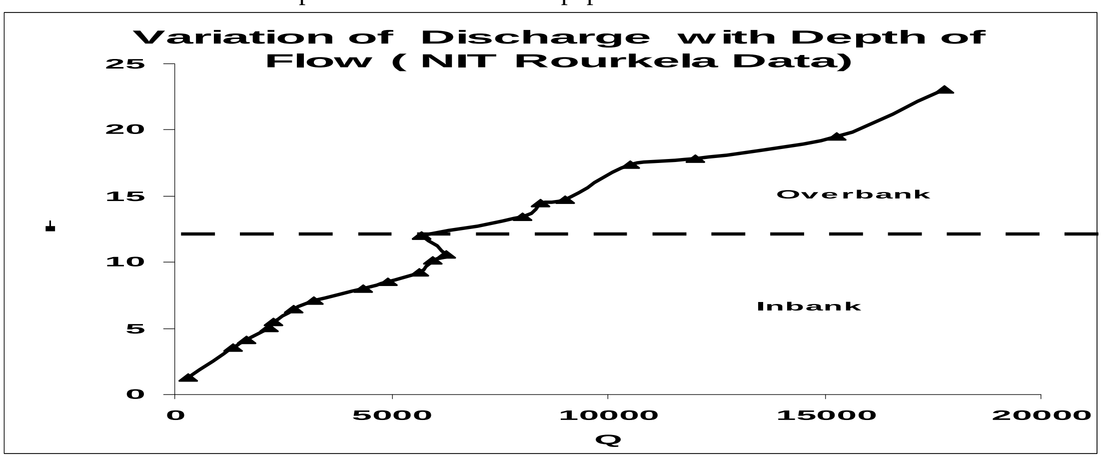
3. Visual estimation of n values can be performed at each site using Barne's (1967) as a guideline.

4. The Cowan (1956) method for estimation of n, as modified by Arcement and Schneider (1989) is designed specifically to account for floodplain resistance given as

$$n = (n_b + n_1 + n_2 + n_3 + n_4)\, m \qquad (7)$$

where n_b is the base value of n for the floodplain's natural bare soil surface; n_1 a correction factor for the effect of surface irregularities on the flood plain (range 0-0.02); n_2 a value for variation in shape and size of floodplain cross section, assumed equal to 0.0; n_3 a value for obstructions on the floodplain (range 0-0.03); n_4 a value for vegetation on the flood plain (range 0.001-0.2); and m a correction factor for sinuosity of the floodplain, equal to 1.0. Values for each of the variables are selected from tables in Arcement and Schneider(1989). This equation was verified for wooded floodplains with flow depths from 0.8-1.5 m.

The above four methods give a general guidance for the selection of n for the surface of a channel. The variation of the selected n values with depth of flow characterizing the loss of energy with flow depth from in-bank to over-bank flow depths as discussed in this paper.



Variation of Manning's *n* with Depth of Flow for Simple Meandering Channel

Sellin et al. (1993), Pang (1998), and Willetts and Hardwick (1993) reported that the Manning's roughness coefficient not only denotes the characteristics of channel roughness but also influences the energy loss of the flow. For highly sinuous channels the values of n become large indicating that the energy loss is more for such channels.

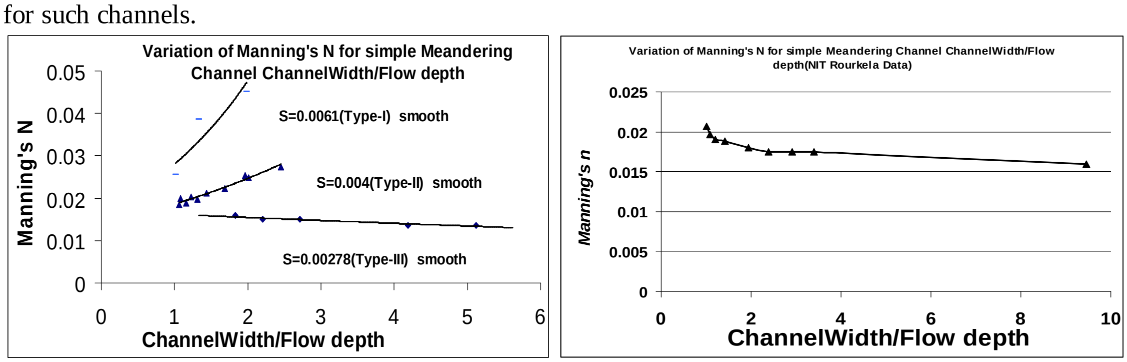


Fig.4 Variation of Manning's *n* with Depth of Flow

The experimental results for Manning's *n* with depth of flow for simple meander channels are plotted in Fig. 4. The plot indicates that the value of *n* increases as the flow depth increases. An increase in the value of *n* can be mainly due to the increase in resistance to flow for wider channel with shallow depth consuming more energy than narrower and deep channel. It can also be seen from Fig. 4 is that steeper channels consume more energy than the flatter channels.

Variation of Manning's *n* with Depth of Flow from Simple to Compound Meandering Channels

The variation of Manning's *n* with depth of flow for the types of channels investigated show a divergent trend (Fig. 5). For the type-I, series-I channel there is a decrease in the value of *n* from run No. 1 to run No. 3 (Fig. 5a). This indicates that the simple meander channel of series - I consume less energy as the depth of flow increases. When the channel overtops and spreads its water to the adjoining floodplain (series-II), a sudden increase in the value of *n* can be noticed. This is mainly due to the increased resistance to flow in the compound section resulting from the interaction of flow between main channel and floodplain. The values of *n* decrease from run No. 1 to run No.2 (Fig. 5a). This is mainly due to the gradual completion of the process of flow interaction between the two depths of flow in the over bank flow situation. At further increase in depth of flow in the floodplain, the results show an increase in the value of *n*. The increase in the value of *n* from run No.2 to run No.3 is due to the reversal of flow interaction. At this depth the floodplain supplies momentum to the main channel.

For simple meander channel of type-II, series-III (Fig. 5b), there is a gradual decrease in the value of *n* with increase in depth of flow from run No.1 to run No. 3. As the flow overtops the main channel and spreads to the floodplain, there is further decrease in the value of *n* from run No. 3, series III to run No.1, series IV. There after the value of Manning's *n* gradually increases to attain a steady state. The variation of Manning's *n* for channel type-II and IIR (Fig. 5c) are nearly similar.

The value of Manning's *n* for the type III channel exhibit an increasing trend (Fig. 5d). For the simple meander channel flow, the increase in Manning's *n* is mainly due to the increase in strength of secondary flow induced by curvature resulting in higher loss of energy. Unlike the previous channels, the geometry and slope of this channel causes an additional loss of energy which continues for the depths of flows investigated. The increase in the value of Manning's *n* from run No. 1 to run No. 3 in the over-bank flow is mainly due to a greater energy loss resulting from the flow interaction between the channel and the floodplain flows for the ranges of depths investigated.

The value of Manning's *n* for the type IV channel exhibit an increasing trend (Fig. 5e). For the simple meander channel flow, the increase in Manning's *n* is mainly due to the increase in strength of secondary flow induced by curvature resulting in higher loss of energy. Unlike the previous channels, the geometry and slope of this channel causes an additional loss of energy which continues for the depths of flows investigated. The increase in the value of Manning's *n* from run No. 1 to run No. 3 in the over-bank flow is mainly due to a greater energy loss resulting from the flow interaction between the channel and the floodplain flows for the ranges of depths investigated.

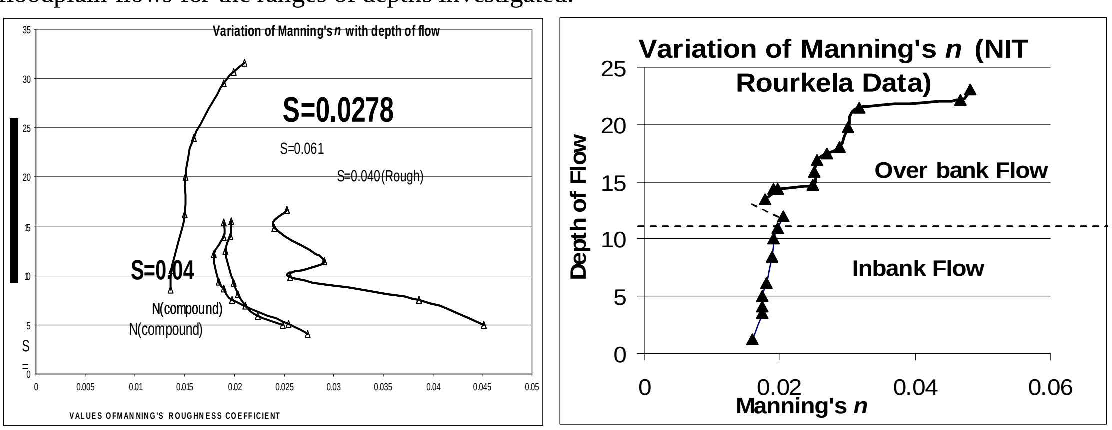


Fig.2 Variation of Manning's *n* with depth of flow from in bank to over bank conditions

For simple meander channel of type-II, series-III (Fig.2b), there is a gradual decrease in the value of *n* with increase in depth of flow from run No.1 to run No. 3. As the flow overtops the main channel and spreads to the floodplain, there is further decrease in the value of *n* from run No. 3, series III to run No.1, series IV. There after the value of Manning's *n* gradually increases to attain a steady state. The variation of Manning's *n* for channel type-II and IIR are nearly similar.

The value of Manning's *n* for the type III channel exhibit an increasing trend (Fig. 2c). For the simple meander channel flow, the increase in Manning's *n* is mainly due to the increase in strength of secondary flow induced by curvature resulting in higher loss of energy. Unlike the previous channels, the geometry and slope of this channel causes an additional loss of energy which continues for the depths of flows investigated. The increase in the value of Manning's *n* from run No. 1 to run No. 3 in the over-bank flow is mainly due to a greater energy loss resulting from the flow interaction between the channel and the floodplain flows for the ranges of depths investigated.

The above discussion indicates that the assumption of an average value of flow resistance coefficient in terms of Manning's *n* for all depths of flow may result in significant errors in discharge estimation.

Variation of Chezy's *C* with Depth of Flow

The variation of Chezy's *C* with depth of flow for the three types of channels investigated is shown in Fig. 3. It can be seen from the figure that the simple meander channel of type-I, exhibits a continuous increase in the value of *C* with depth of flow. A sudden decrease in the value of *C* can be noticed when the flow spills over to the floodplains (Fig. 3a). As the depth of flow in the floodplain increases, the value of *C* also increases and tries to attain a steady state.

For the type-II channel when the flow is confined to meander section only (series II), a gradual increase in the value of *C* can be noticed from run No -1 to run No.5 (Fig. 3b). Unlike the previous channel, the change in the value of *C* is not sudden when the water spills over to the floodplain. The channel is expected to give a steady value of *C* at still higher depths of flow in the floodplain. It can be seen that the parameter *C* for the channel type - II and II R are similar.

Channel type - III shows a gradual decrease in the value of Chezy's *C* from run No. 1 to run No. 5 in series VII, when the flow is confined to simple meander channel only (Fig. 3c). A sudden decrease in the value of *C* is noticed, when the flow spills over to the floodplain. It is expected that the value of *C* will decrease further and reach a steady state at still higher depths of flow in the floodplain. For this channel, the decrease in Chezy's *C* is mainly due to the increase in strength of secondary flow induced by curvature resulting in higher loss of energy.

It seems that the geometry of channel of types - I, II and II R and their higher bed slope with respect to type-III channel are in a position to balance the additional loss of energy induced by curvature. That is why type-I, II and II R channels show a continuous increase in the value of *C* with depth, both for in-bank and over-bank flow situations.

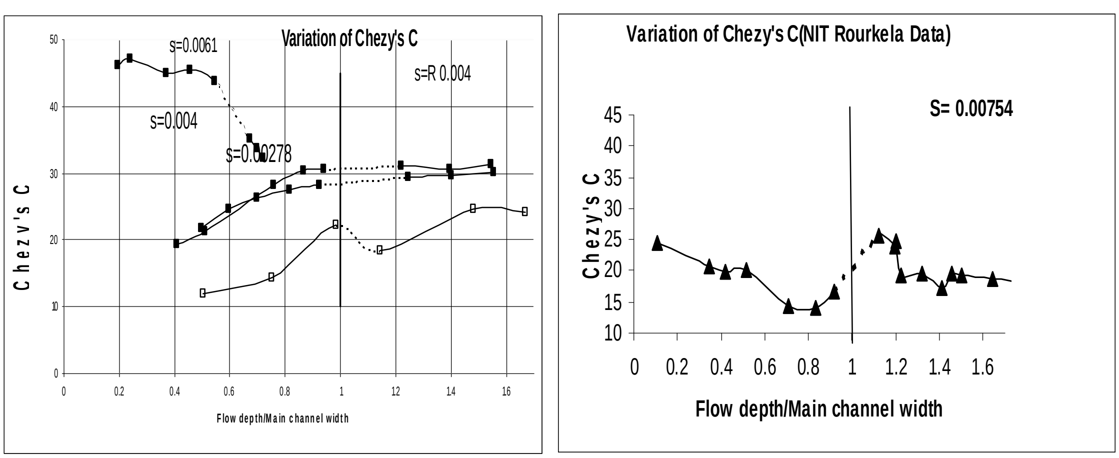


Fig.3 Variation of Chezy's *C* with depth of flow from in bank to over bank conditions

Variation of Darcy-Weisbach Friction Factor *f* with Depth of Flow

The variation of friction term *f* with depth of flow for the channel types I, II, IIR and III is shown in Fig.4. The behavioral trend of friction factor *f* is nearly similar to that of the variation of Manning's *n*.

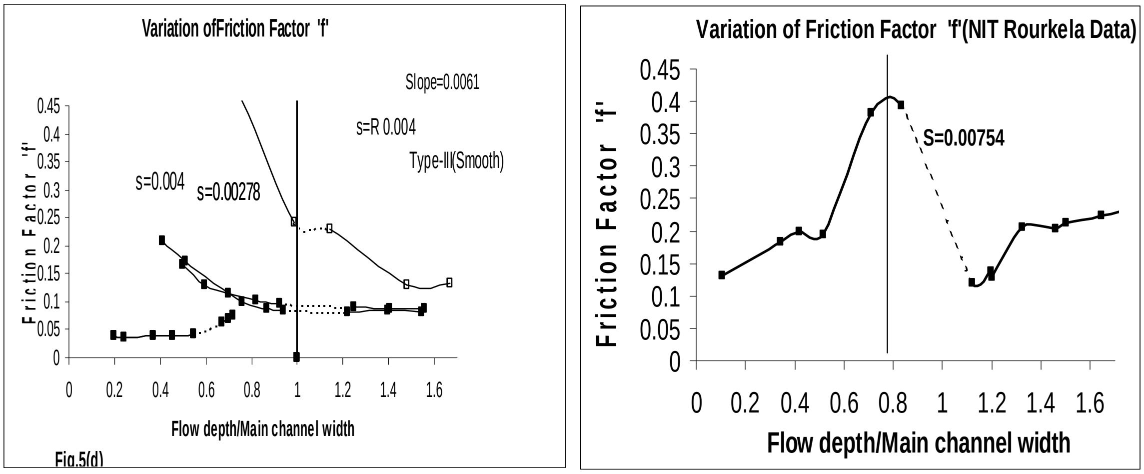


Fig.4 Variation of Darcy-Weisbach Factor *f* with depth of flow from in bank to over bank flow

1. The flow resistance changes abruptly at the bankfull stage, and varies significantly with depth. For overbank flow, it generally increases as the flow depth increases,
2. Manning's or Chezy's coefficient *n* not only denotes the roughness characteristics of a channel but also the energy loss of the flow. It is an established fact that the influences of all the forces that resist the flow in an open channel are assumed to have been lumped to a single coefficient *n.*
3. Even for simple meandering channels carrying in bank flows, these coefficients are found to vary with depth of flow in the channel. Manning's *n* is found to decrease with depth for narrow channels while for wide channels it is found to increase with depth of flow in the channel. The behaviour of Manning's *n* is also found to be erratic in the over bank flow conditions for the three types of channels investigated.
4. The coefficients for Chezy's *c* and Darcy-Weisbach *f* friction factors from in bank flow to over bank flow are found to be in line with the behaviour of Manning's *n*.
5. The assumption of an average value of flow resistance coefficient in terms of Manning's *n* for all depths of flow may result in significant errors in discharge estimation.
6. No trend in the energy loss parameter $\sqrt{S_f}/n$ could be established for the five types of channels investigated when plotted for their values ranging from in bank to over bank flows.
7. The interaction of flow between the main channel and floodplain, the channel size, shape, and slope are found to influence the coefficients *n*, *c*, and *f* more than the other forces.
8. The main reason for discharge decrease in the main channel and increase in the floodplain is because of the change in energy distribution in the flow field. The river flow consumes more energy in the main channel and less energy in the floodplain. When the river flow consumes more energy, it also passes less discharge. On the contrary, when the flow consumes less energy, it passes more discharge.

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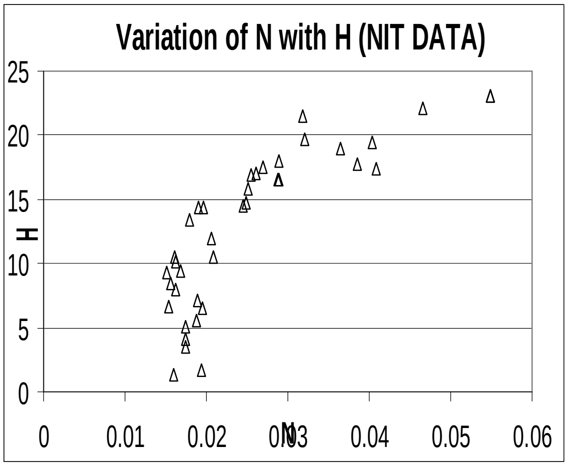


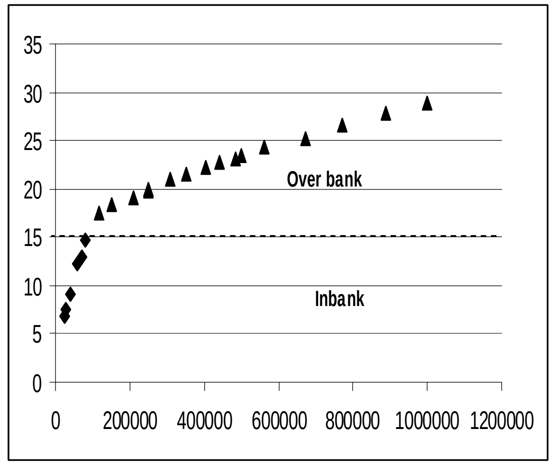
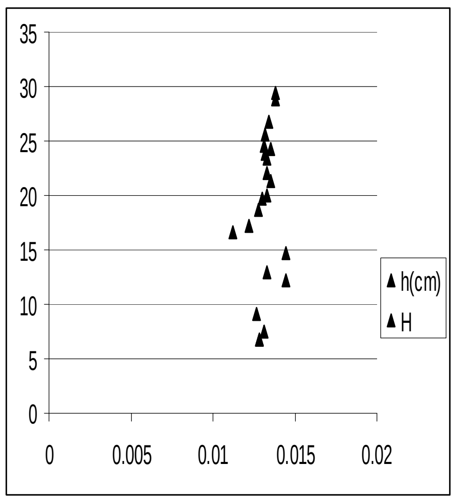
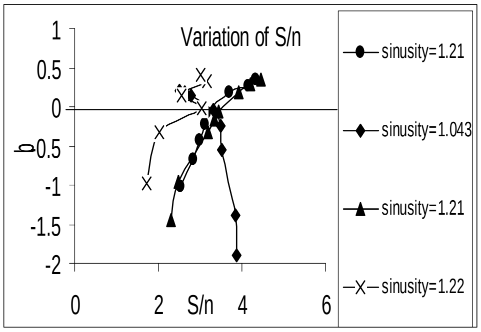
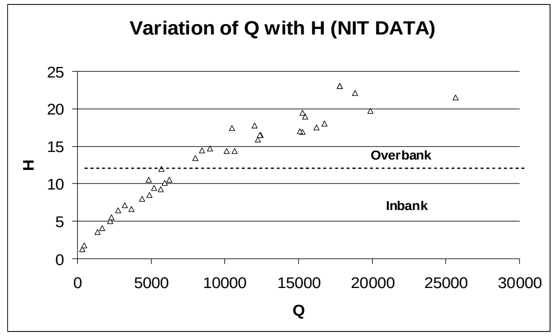


Fig. 5 Variation of Manning's *n* with depth of flow from in bank to over bank conditions







EXPERIMENTAL STUDY OF STAGE-DISCHARGE - RESISTANCE RELATIONSHIPS IN A COMPOUND CHANNEL

Abstract:

Keywords: overbank flow, compound channel, sediment transport, flow resistance

1 INTRODUCTION

Our understanding of alluvial hydraulics is still not very good, even for uniform and inbank flows. Our understanding of flood flows and morphological response is inevitably weaker, mainly due to the complexity of two-phase flow and the difficulty of measurement under extreme conditions. However, in the last few decades, a considerable amount of research has been undertaken on over bank flows, especially concerning the main channel/floodplain interaction effect on the conveyance capacity of the channel, the flow resistance, and the proportional distribution of discharge between the main channel and any associated floodplains. Knight & Shiono (1996) and Knight (1999). Of the several methods for predicting the stage-discharge relationship in compound channels, the 1-D model developed by Ackers (1993) and the analytically based solution to the depth-averaged Navier-Stokes equation, developed by Shiono & Knight (1991), are perhaps among the most promising methods currently available.

flow with the main channel flow and its impact on the flow resistance, and channel geomorphology, most studies have been carried out with smooth floodplains. In order to rectify this, a systemic series of laboratory experiments have recently been conducted in a compound channel with different floodplain roughnesses, and are the subject of paper. Particular attention is paid to the stage-discharge relationships, the variation of resistance with depth.

Experimental setup:

The experiment concerning the flow in simple meander channel and compound meander channel have been conducted at the Hydraulic Engineering Laboratory of the Civil Engineering Department, National Institute of Technology, Rourkela, Orissa. Inside a tilting flume a compound

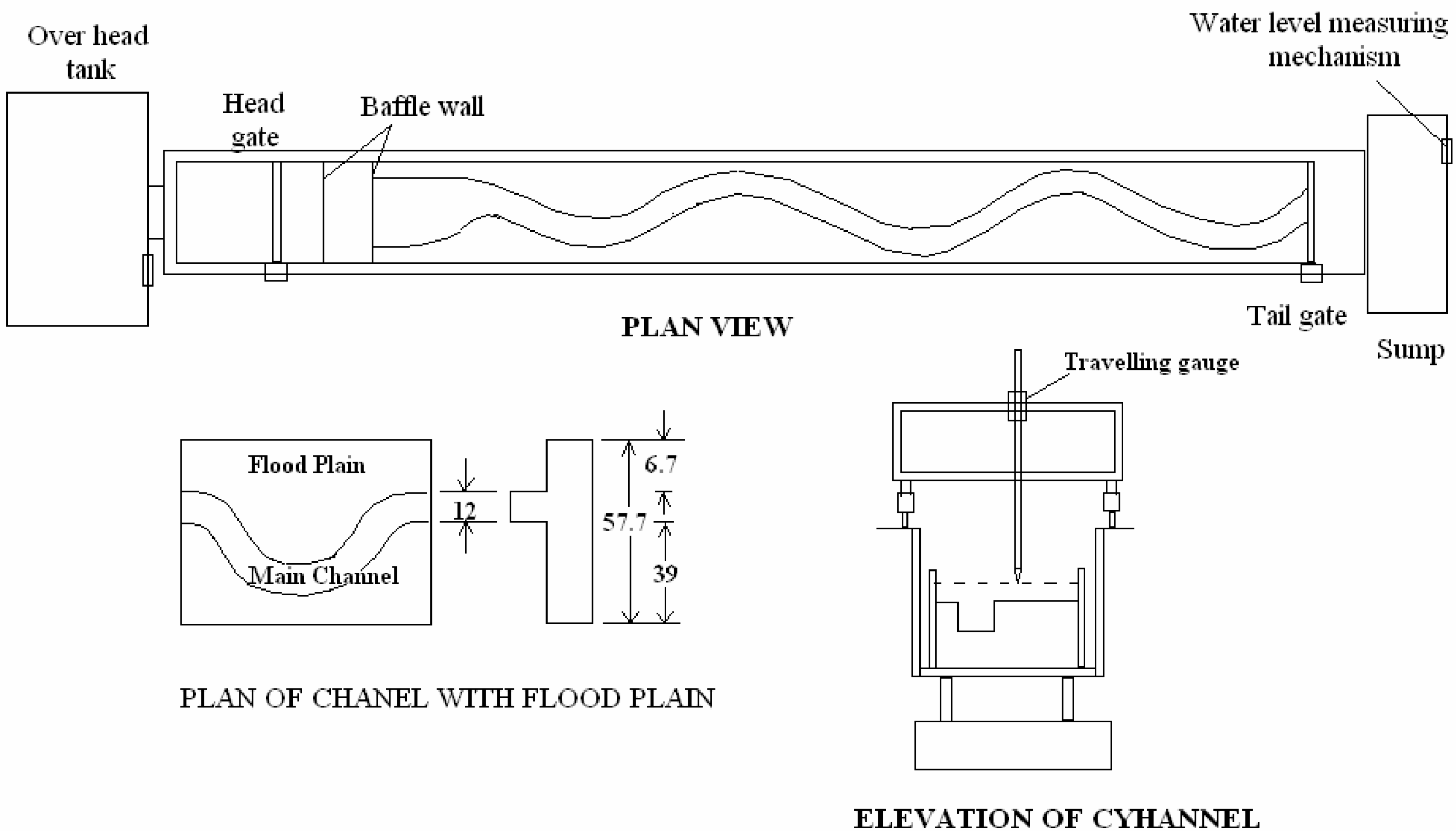
channel consisting of meandering main channel with flood plains is fabricated. The channel surfaces made of Perspex sheet, which is taken as smooth boundary. The tilting flume is made up of metal sheet but the wall are of glass. The tilting set-up is 12 m long, 0.6 m wide and 0.6 m deep.

Water is supplied to the experimental channel from an overhead tank. An overflow arrangement in the overhead tank enables to draw water with constant flow head. The stilling tank located at the upstream of the channel has two baffle walls to reduce the turbulence of the incoming water. An arrangement of tail gate is there for making the flow uniform . From the sump water is pumped back to the overhead tank, thus setting complete re-circulating system of

water supply for the experimental channel. The discharge is measured by volumetric method. The water is collected in a rectangular tank, for different time space depth rise in that tank is measured. Minimum time space taken is from 30 sec to 2 mins. Then by that velocity of flow is calculated. flow depth is measured by sliding point gauge. Discharge for each flow depth is taken.

In case of simple meander channel Manning's roughness co-efficient is mainly dependent on slope, sinuosity and aspect ratio. Aspect ratio is the ratio of width of channel to depth of flow.

The experiments were performed in a tilting 12m long flume with a test length of 9.5m at the University of Birmingham. The flume was 1213 mm wide, and configured into a two stage channel with a 398mm wide, 50mm deep sand main channel and two 407.3mm wide floodplains, as shown in Fig. 1. The flume had a water circulation system, where the water was supplied through 50mm, 100mm and 150mm pipelines, with discharges measured by an electro-magnetic flow meter, a Venturi meter and a Dall tube respectively. Sand, with a d_{35} = 0.80mm was re-circulated in the flume via a slurry pump and the 50mm pipeline. Water surface profiles were measured directly using pointer gauges, and uniform flow was set up through adjustments to three tailgates until the mean water surface slope was equal to the valley slope of the floodplain, fixed at 2.204×10^{-3}. A preliminary development of bed was allowed for in establishing normal depth flow. For a required test discharge, preliminary experiments were undertaken and the tailgates were calibrated so that the mean water surface slope and the mean longitudinal bed slope would be set equal to the valley slope of the channel, fixed at 2.024×10^{-3}. These settings were found be very reliable and the experiments could be repeated at will. During each experiment measurements were made of velocity and transport rates. Velocity measurements were taken at 0.4 of the local depth on the sand main channel and the floodplains. Sediment samples were collected manually over 5 ~ 6 minute intervals for at least 5 times for each experiment whilst the dune migrations movements are recorded manually over at least 1 hour. For large discharges, bed profiles were also measured at the conclusion of each experiment with an automatic touch-sensitive bed profiler.



Schematic diagram showing the experimental setup

3 EXPERIMENTAL RESULTS

STAGE-DISCHARGE RELATIONSHIPS

It is of interest to compare the differences between the stage-discharge relationships for alluvial channels with inbank and overbank flows with different floodplain roughness. The measured H~Q relationships are shown in Fig. 3, with the experimental data for rigid compound channels (Khatua&Patra, 2006) included as well. In each case, the data are best fitted by a power function, in a form of $H = \alpha Q^{\beta}$, where α and β are constants, given in Table 1, in which H is the flow depth (m) and Q is the discharge (m^3/s). As can be seen from Fig. 3, there is not a

Table 1 Values of α and β of H~Q relationships

Flow	Main channel	Floodplain	α	β	Correlation coefficient
Inbank (isolated)	Mobile	-	2.7399	0.8273	0.9979
Overbank	"	smooth	0.3617	0.4092	0.9985
"	"	λ = 3 m	0.5781	0.5072	0.9942
"	"	λ = 1 m	1.1665	0.6634	0.9972
"	"	λ = 0.5 m	1.8011	0.7601	0.9960
"	"	λ = 0.25 m	2.2496	0.8022	0.9963
"	Rigid	smooth	0.2670	0.3672	0.9973

discontinuity in the H~Q relationship at the bankfull depth of 0.05m for compound channels with mobile beds, whereas comparable data for rigid compound channels do show sharp discontinuities, as reported by Knight & Demetriou (1983), Knight, Shiono & Pirt (1989), Atabay & Knight (1999) and Myers et al. (1999). As would be expected, the discharges are reduced for mobile bed channels compared with the rigid channels, for both inbank and overbank flows. Furthermore, for the mobile bed compound channels, the discharge decreases as the roughness on the floodplains increases for the same flow depth.

4 RESISTANCE RELATIONSHIPS

Standard hydraulic laws were used to represent the resistance to flow, as used by most practising engineers, given by the following equivalent forms:

$$U = R^{2/3} S^{1/2} / n \qquad \text{or} \qquad U = [(8g/f)\ RS\ ]^{1/2} \tag{1}$$

where U is the channel mean velocity, R is the hydraulic radius, S is the friction slope (equal to the valley slope S_o for uniform flow), g is the gravitational acceleration, and n & f are the Manning and the Darcy-Weisbach resistance coefficients respectively.

The experimental results for n are shown in Fig. 4, together with some data for the rigid channels for the purpose of comparison. Figs. 4 shows that the resistance coefficient has an abrupt transition at the bankfull stage, whether the channel is rigid or mobile. The overall values of n (and f) are much larger for the mobile channels than for the rigid channels at the same flow depth. In the mobile bed cases, n increase as the roughness of the floodplain increases, i.e. λ from infinity (smooth) to 0.25 m (roughest).

5 VELOCITY DISTRIBUTION AND ZONAL DISCHARGE RELATIONSHIPS

The lateral distribution of mean streamwise velocity was measured over the cross-section, including the sand-bed main channel and the rigid floodplains. A typical transverse velocity distribution is shown in Fig. 5, which shows that the velocity distribution is symmetric, and that there is a minimum value around the centre of the main channel.

The zonal discharges can be calculated by integrating the velocity data over the cross-section. The proportions of the total flow within the main channel and on the floodplains were thus determined and are shown in Fig. 6 for both smooth and rough cases. Despite some scatter in the data, largely due to the effect of dune movement, certain trends are apparent. The best-fit equations through the data for the proportion of flow occurring on the floodplain are:

Smooth:

$$Q_{fp}\% = -435.03\, Dr^3 + 352.63\, Dr^2 + 40.167\, Dr - 0.3645 \qquad R^2 = 0.9851 \qquad (2)$$

Rough:

$$Q_{fp}\% = a\, Dr^2 + b\, Dr + c \qquad (3)$$

Where

λ	a	b	c	R^2
3 m	3.0117	90.355	-0.5585	0.9802
1 m	14.099	66.092	0.1160	0.9796
0.5m	36.177	44.553	0.1224	0.9974
0.25m	-40.46	66.19	-0.8939	0.9217

and $Dr = (H-h)/H$, $Q_{fp}\% = Q_{fp}/Q_t \times 100$, Q_{fp} = the discharge on the floodplain, and Q_t = the total flow. Thus the proportion of main channel discharge, $Q_{mc}\%$, can be obtained from

$$Q_{mc}\% = 100 - Q_{fp}\% \qquad (4)$$

As might be expected, Fig. 6 clearly indicates that the proportion of discharge in the main channel increases as the roughness of the floodplain increases.

Sediment Transport Rates and Bed Forms

An important objective of these experiments was to investigate how the flow structure affects the sediment transport rate. The determination of the sediment transport rate is important in river engineering because it governs the behaviour of the river bed. It also helps in understanding the non-equilibrium state, and in specifying the sediment capacity of a channel once an equilibrium state is reached.

The measured sediment transport rates, expressed either in term of weight per second, G_s (g/s) or ppm, X, are shown in Fig. 7 and Fig. 8 respectively, where the sediment transport rates are shown plotted against the total discharge, Q_t. As can be seen from these Figures, G_s increases as the flow rate increases, but X (ppm) only increases up to around the bankfull stage, after which it gradually decreases with increasing overbank flow. As would be expected, G_s decreases as the roughness of the floodplain increases. A preliminary analysis on the measured data gives the following function:

$$\ln G_s = k_1 + k_2 \ln Q + k_3 / Q \qquad (5)$$

where G_s is in g/s, Q is in m^3/s and the coefficients are as follows:

λ	k_1	k_2	k_3	R^2
Inbank	3.5455	0.3355	-0.0082	0.9892
smooth	1.0765	-0.2529	-0.0113	0.9786
3 m	0.9442	-0.2577	-0.0106	0.9947
1 m	1.4836	-0.0679	-0.0080	0.9895
0.5m	1.3102	-0.0919	-0.0077	0.9770
0.25m	0.2744	-0.3460	-0.0093	0.9802

For an alluvial river various bed forms, such as ripples, dune, bars and riffles, occur on the channel bed, depending on the intensity of the flow. Ripples are small bed forms and occur during very low flows. Dunes are more common, and are much larger than ripples but smaller than bars and riffles. The dimensions of a typical dune were found for all the experiments, as indicated in Fig. 9. This Figure shows that for a comparable discharge, the dune size for the compound channel with a roughened floodplain is much bigger than that for the channel with a smooth floodplain. The data also shows that the dune height increases as the floodplain roughness increases, for the more or less same discharge.

Fig. 1 Schematic cross section of the flume at University of Birmingham

Fig. 2 Schematic of metal mesh for the roughness on the floodplain

Fig. 3 Comparison of H~Q relationship for mobile compound channels with smooth & rough floodplains

Fig. 4 Relationship of manning's coefficient (n) versus flow depths

Fig. 5 Laterial variation of depth-averaged velocity (Ud) with a roughened loodplain (λ=0.25m)

Fig. 6 Zonal discharge percentage (%Q) for mobile compound channels with rough floodplains

Fig. 7 Comparison of sediment transport rate G_s for smooth & rough floodplains

Fig. 8 Sediment concentration vs discharge for smooth & rough floodplain compound channel

Fig. 9 Standarised bed level variance for the smooth (Q=27.15l/s) and rough (λ=3m, Q=27.20l/s) floodplains

Analysis of experimental data

Simple Channel:

Slope: 0.000966

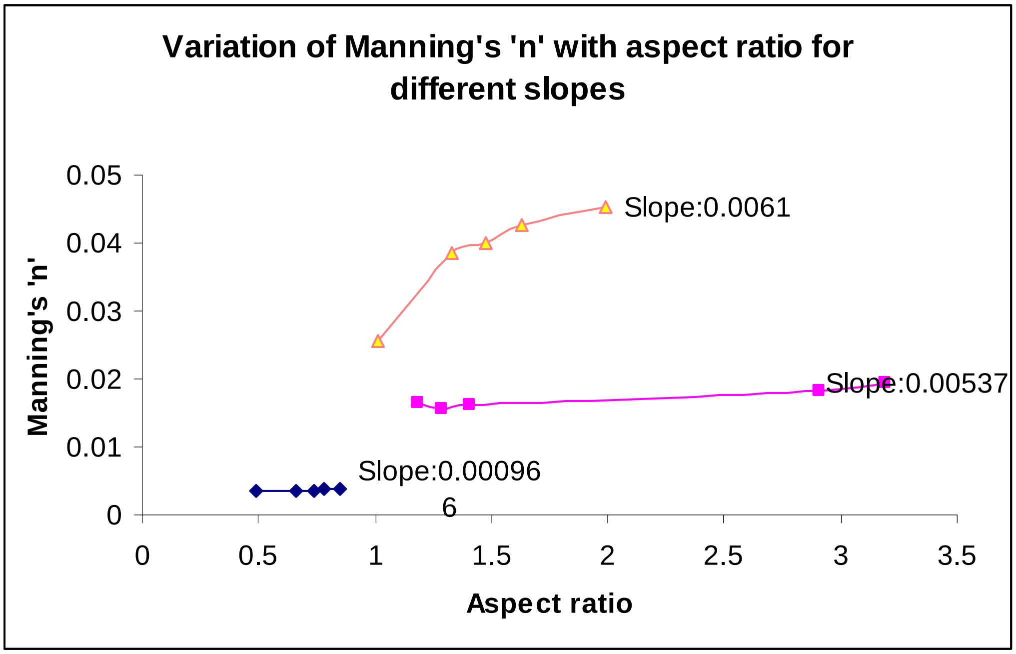
Aspect ratio (δ)	**Manning's roughness co-efficient (n)**
0.85	**0.0038**
0.78	**0.0037**
0.74	**0.0036**
0.66	**0.0035**
0.49	**0.0035**

Slope: 0.00537

Aspect ratio (δ)	**Manning's roughness co-efficient (n)**
3.19	**0.0194**
2.91	**0.0181**
1.41	**0.0162**
1.29	**0.0156**
1.18	**0.0166**

Slope: 0.0061

Aspect ratio (δ)	**Manning's roughness co-efficient (n)**
1.015	**0.0256**
1.329	**0.0386**
1.476	**0.0401**
1.631	**0.0427**
1.988	**0.0452**



In case of simple channel Manning's roughness co-efficient varies with different parameters that has discussed earlier in procedure part. With aspect ratio Manning's 'n' also varies. Aspect ratio and Manning's 'n' are directly related to each other. Increase in aspect ratio means decrease in depth of flow for constant width of the channel. In a fixed set-up width of channel cannot be varied. Less depth means resistance offered by channel bed is more per unit of flow. Similarly when depth of flow increases then resistance offered by the channel bed per unit of flow decreases due to that with increase of aspect ratio Manning's roughness co-efficient increases for different slopes. For mild slope increment is less. As slope increases then increment of roughness is also more. From the trends of all the curves it is clear that after a large value of aspect ratio roughness value becomes parallel to x axis means roughness value does not increase with aspect ratio.

Compound Channel:

Slope: 0.000966

Relative depth (β)	**Manning's roughness co-efficient (n)**
0.107	**0.0033**
0.195	**0.0035**
0.242	**0.0036**
0.322	**0.0038**
0.334	**0.0040**
0.505	**0.0041**

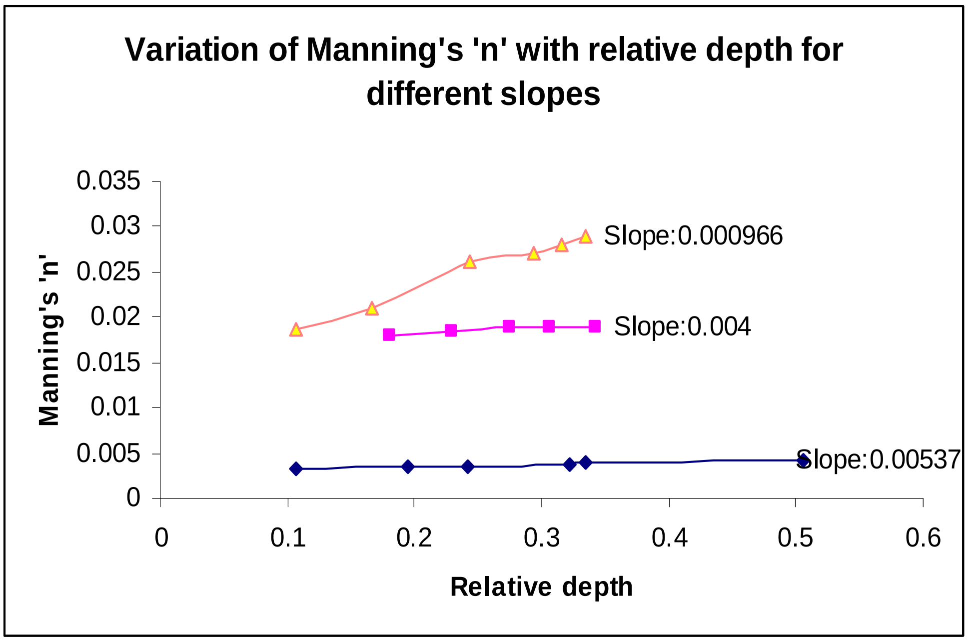
Slope: 0.004

Relative depth (β)	**Manning's roughness co-efficient (n)**
0.18	**0.0179**
0.23	**0.0184**

0.275	**0.0188**
0.307	**0.01885**
0.343	**0.0189**

Slope: 0.00537

Relative depth (β)	Manning's roughness co-efficient (n)
0.107	**0.0187**
0.167	**0.0211**
0.244	**0.0261**
0.293	**0.027**
0.315	**0.028**
0.334	**0.029**



Analysis of experimental data sets

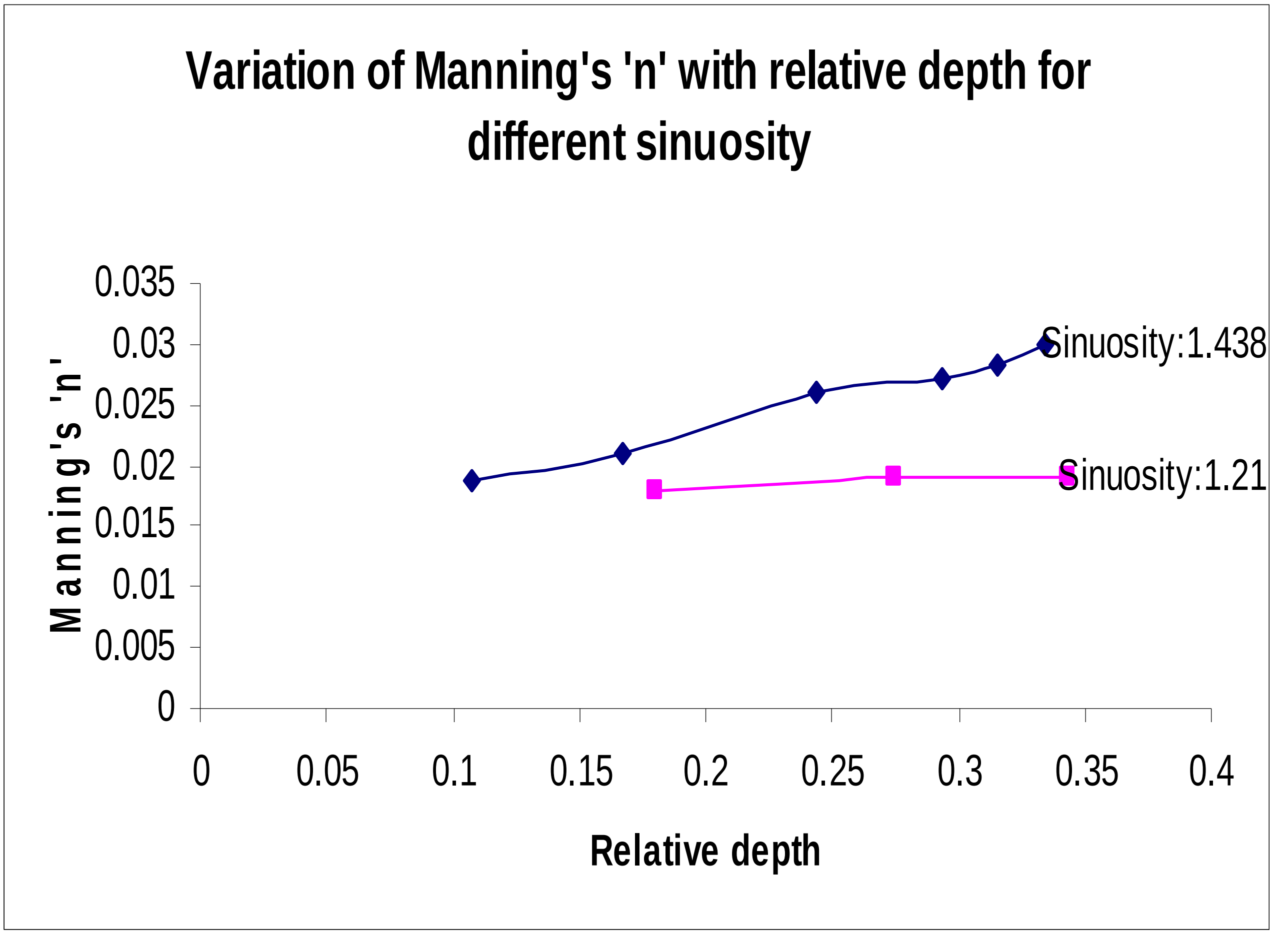
Sinuosity:1.438

Relative depth (β)	Manning's roughness co-efficient (n)
0.107	**0.0187**
0.167	**0.0211**
0.244	**0.0261**
0.293	**0.027**
0.315	**0.028**
0.334	**0.029**

Sinuosity:1.21

Relative depth (β)	Manning's roughness co-efficient (n)

0.181	**0.0191**
0.27	**0.0195**
0.343	**0.0197**



As the value of sinuosity (Sr) increases Manning's roughness co-efficient (n) also increases with relative depth (b). Sinuosity more means more bend is present in channel length. As bend in a channel is more then more resistance to flow is there that is offered by that bend. Manning's roughness co-efficient is nothing but the resistance offered by the bed of a channel. Due to the above mentioned reason Manning's roughness co-efficient increases.

Co-relation of R and sinuosity (S_r) with Manning's roughness co-efficient

Manning's 'n'	**R**	**Sinuosity (S_r)**
0.015	**0.0725**	**1.043**
0.0179	**0.2452**	**1.21**
0.018	**0.1781**	**1.22**

0.019	**0.2790**	**1.438**
0.036	**0.825**	**3.000**

Value of co-relation between R and sinuosity (S_r) is 99.03
Value of co-relation between Manning's 'n' and sinuosity (S_r) is 99.74
Value of co-relation between Manning's 'n' and R is 99.29

As both R and sinuosity (S_r) are very good co-related with Manning's roughness co-efficient (n). So we can take any one of them as a dependent for the determination of Manning's roughness co-efficient but as sinuosity is more related than R so here sinuosity (S_r) is taken as dependent one.

Simple channel:

$$n = 728.45 \text{ X } n_b \text{ X } S_r \text{ X } S^{1.2444} \text{ X } (-0.0036\delta^5 + 0.073\delta^4 - 0.5077\delta^3 + 1.4559\delta^2 - 1.5679\delta + 1.4931)$$

$1.3 < S_r < 1.5$

$$n = 524.83 \text{ X } n_b \text{ X } n_b \text{ X } S_r \text{ X } S^{1.2444} \text{ X } (-0.0144\delta^5 + 0.292\delta^4 - 2.03\delta^3 + 5.82\delta^2 - 6.27\delta + 5.97)$$

$1.0 < S_r < 1.3$

Calibration in case of simple channel for sinuosity 1.438

Observed 'n'	**Predicted 'n'**
0.015644	**0.015599**
0.016254	**0.01603**
0.016691	**0.015216**
0.01817	**0.019315**
0.019401	**0.01875**
0.01693	**0.017287**
0.01809	**0.01911**
0.0191	**0.018199**

Statistical analysis of predicted and observed Manning's roughness co-efficient

Modeling efficiency = 0.6795

Index of agreement = 0.9281

RMSE = 7.48 X 10^{-4}

MAE = 5.88 X 10^{-4}

Co-efficient of determination = 0.797

Compound channel:

$n = 21.6591 \times n_b \times S_r \times e^{0.1097\alpha} \times S^{0.3471} \times (69.13\beta^4 - 50.454\beta^3 + 7.555\beta^2 + 0.9761\beta - 0.0009)$
For Slope<= 0.001

$n = 48.03 \times n_b \times S_r \times e^{0.1097\alpha} \times S^{0.3471} \times (69.13\beta^4 - 50.454\beta^3 + 7.555\beta^2 + 0.9761\beta - 0.0009)$
From slope 0.001 to 0.0061

Calibration in case of straight compound channel for slope less than 0.001

observed n	predicted n
0.00339	0.00335
0.00399	0.00396
0.00366	0.00364
0.00395	0.00397
0.0037	0.00367
0.00375	0.00367
0.00391	0.00399
0.0038	0.00391
0.00369	0.00363
0.00394	0.00387

Statistical analysis of predicted and observed Manning's roughness co-efficient

Modeling efficiency = 0.873

Index of agreement = 0.971

RMSE = 6.13 X 10^{-5}

MAE = 5.4 X 10^{-5}

Co-efficient of determination = 0.9998

Calibration in case of meander compound channel for slope greater than 0.001

observed n	predicted n
0.02819	0.03044
0.02997	0.02823
0.01873	0.01963
0.018	0.01799
0.0283	0.02767
0.03	0.02927
0.0151	0.01489
0.02987	0.03001