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BOUNDARY SHEAR STRESS DISTRIBUTION IN MEANDERING COMPOUND CHANNEL FLOW

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ABSTRACT: *Reliable prediction of boundary shear force distributions in open channel flow is crucial in many critical engineering problems such as channel design, calculation of energy losses and sedimentation. During floods, part of the discharge of a river is carried by the simple main channel and the rest are carried by the floodplains located to its sides. For such compound channels, the flow structure becomes complicated due to the transfer of momentum between the deep main channel and the adjoining floodplains which magnificently affects the shear stress distribution in flood plain and main channel sub sections. Knowledge of momentum transfer in different interfaces starting from the junction between main channel and flood plain can be acquired from the distribution of boundary shear in the sub sections. An investigation concerning the distribution of shear stress in the main channel and floodplain of meandering and straight compound channels are presented. Based on the experimental results of boundary shear, this paper predicts the distribution of boundary shear carried by main channel and flood plain sub sections of meandering and straight compound channels. Five dimensionless parameters are used to form equations representing the total shear force percentage carried by floodplains. A set of smooth and rough sections is studied with aspect ratio varying from 2 to 5. The model are also validated using the data of other investigators.*

Key words: Boundary shear, Aspect ratio, Rectangular channel, Interface plane, Compound Section, FloodPlain, Meander, Over-bank flow, Apparent shear,

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INTRODUCTION

Information regarding the nature of boundary shear stress distribution in a flowing simple and compound channels is needed to solve a variety of river hydraulics and engineering problems such as to give a basic understanding of the resistance relationship, to understand the mechanism of sediment transport and to design stable channels etc. The boundary shear stress distribution, velocity distribution and flow resistance in compound cross section channels have been investigated by a number of authors **(**Wright and Carstens 1970, Ghosh and Jena 1971, Myers, and Elsawy 1975, Rhodos and Lamb 1991, Rhodos and Knight 1994, Knight and Cao 1994, Patra and Kar 2000, Patra and Kar 2004). Most of hydraulic formulae assume that the boundary shear stress distribution is uniform over the wetted perimeter. Distribution of boundary shear stress mainly depends upon the shape of the cross section and the structure of the secondary flow cells. However, for meander channel - floodplain geometry, there is wide variation in the local shear stress distribution from point to point in the wetted perimeter. Also the magnitude of boundary shear of a meandering channel is significantly different from that of straight channel having the same geomotry, shape and cross sectional area.Therefore, there is a need to evaluate the boundary shear stress carried by the main channel and floodplain walls at various locations of meander path. The aim of this study is to describe the effect of the interaction mechanism on the basis of shear stress distribution in meandering and straight compound channel sections.

EXPERIMENTAL SETUP

Experimental data from three types of channels are presented in this paper. Schematic diagram showing experimental set up along with the plan forms of the meandering channels with floodplains are shown in Fig.1. The summery of experimental runs for the meandering compound channel geometries are given in Table 1. 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. Type-III channel is symmetrical with two equal floodplains attached to both sides of the main channel. A recirculating system of water supply is established with pumping of water from an underground sump to an overhead tank from where water could flow under gravity through a sharp-crested V-notch measuring device to a stilling tank. From the stilling tank water is led to the experimental channel through a baffle wall, and a transition zone helped reduce turbulence of the water flow. An adjustable tailgate at the downstream end of the flume is used to achieve uniform flow over the test reach in the channel for a given discharge. Water from the channel is collected in a tank from where it was pumped back to the system. The measuring devices consist of a point gauge mounted on a traversing mechanism to measure depths having a least count of 0.1 mm. A Preston micro-Pitot tube in conjunction with a water manometer is used to measure dynamic pressures for the evaluation of boundary shear stress and velocity. The tube is fabricated locally according to the design used by Ippen and Drinker (1962).

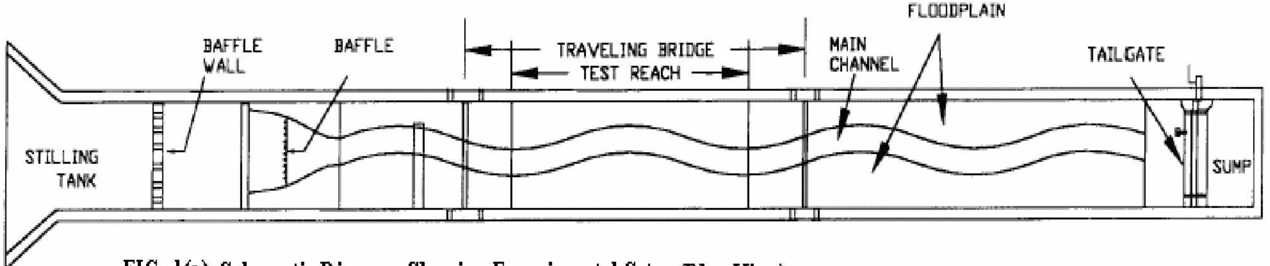
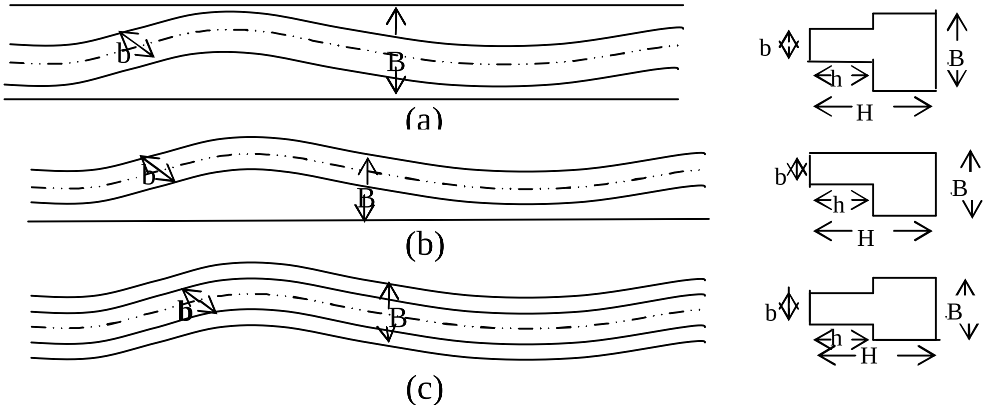


FIG. 1(a) Schematic Diagram Showing Experimental Setup (Plan View)



(a)

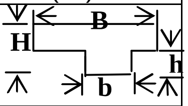
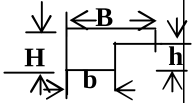
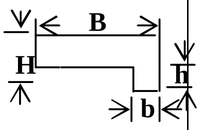
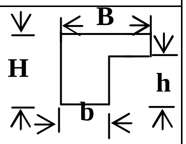
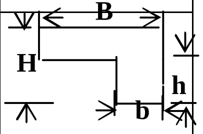
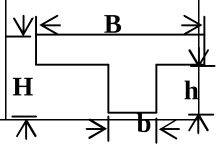
(b)

(c)

FIG. 1(b) Plan Forms of Meandering Experimental Channels with Floodplains

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 are identical. The observations are made at the section of maximum curvatures (bend apex) of the meandering channel geometries. Experiments are conducted utilizing the facilities available at the Water Resources and Hydraulic Engineering Laboratory of the Civil Engineering Department of the Indian Institute of Technology, Kharagpur India. For each channel, boundary shear stress measurements at three locations in the meander path covering a number of points in the wetted perimeter for each location have been obtained from the dynamic pressure drop measured by Preston tube - micro manometer system and also from the semi log plot of velocity distribution. Estimation of boundary shear stress by Preston tube technique provides a simple, reliable and quicker alternative involving the recording of the dynamic pressure drop along the flow boundary. The diameter of the Preston tube used is such that it lies in the region of dynamic similarity, which is about one-fifth of the boundary layer thickness. In other words, the diameter of the tube has great influence on the shear measurement at the channel bed. While dealing with the flow over rough boundaries care has been taken to locate the tube from zero datum such that the roughness distribution does not influence the recording of the dynamic pressure drop. In view of the complexities involved in converting the dynamic pressure drop to shear stress, the computed mean shear by both the approaches are compared with the energy gradient approach and the closest values of shear distribution are considered for the study. While calculating the shear stress, the value of Von Karman's constant *k* is taken as 0.40 for both smooth and rough boundary. Though the general pattern of distribution of shear stress by both the methods is somewhat similar, there exist some local variations in the approaches. One reason for the disagreement of local shear stress can be the error in computing the local shear velocities from velocity profiles at these locations.

Table 1. Summary of Experimental Runs for Meandering Channel with Floodplains

Experi -ment series/ Run No	**Nature of Channel surface**	**Bed slope**	**Top width *B*(cm)**	**Main channel width *b*(cm)**	**Total depth of Flow *H*(cm)**	**Depth of lower main channel h(cm)**	**Sinuo-sity S_r**	**Amplitude/ Width ratio (*R*)**	**Observed Discharge (cm^3/sc)**	**%age of flood plain shear (% S_{fp})**	**Shape of the compound channel section**
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
A.1 A.2 A.3	smooth smooth smooth	0.0061 0.0061 0.0061	52.5 52.5 52.5	10 10 10	11.6 14.9 16.8	10 10 10	1.22 1.22 1.22	0.178 0.178 0.178	3960 14000 19500	64.1 67.0 67.4	
C.4 C.5 C.6	smooth smooth smooth	0.004 0.004 0.004	21.3 21.3 21.3	10 10 10	12.19 13.81 15.24	10 10 10	1.21 1.21 1.21	(-)0.481 (-)0.481 (-)0.481	5800 8450 11200	29.0 34.8 38.0	
D.7 D.8	smooth smooth	0.004 0.004	41.8 41.8	10 10	12.19 14.08	10 10	1.21 1.21	0.245 0.245	5800 8450	59.2 59.9	
F.9 F.10 F.11	rough rough rough	0.004 0.004 0.004	21.3 21.3 21.3	10 10 10	12.22 13.71 15.24	10 10 10	1.21 1.21 1.21	(-)0.481 (-)0.481 (-)0.481	5500 8200 10900	27.1 34.4 36.1	
G.12 G.13 G.14	rough rough rough	0.004 0.004 0.004	41.8 41.8 41.8	10 10 10	12.49 14.23 15.84	10 10 10	1.21 1.21 1.21	0.245 0.245 0.245	5500 8200 10900	55.9 56.0 60.0	
I.15 I.16 I.17	smooth smooth smooth	0.00278 0.00278 0.00278	138 138 138	44 44 44	29.5 30.7 31.6	25 25 25	1.043 1.043 1.043	0.072 0.072 0.072	94535 103537 108583	37.1 42.8 46.1	

BOUNDARY SHEAR FORCE RESULTS

The shear stress distribution for two typical channels (Table 1) A-3 and C-6 are shown in Fig.2 (a) and Fig.2 (b) respectively. Various boundary elements of the compound channels are labeled from

1– 4 in Fig. 4. Label (1) denotes the vertical wall(s) of floodplain with length [$2(\tilde{H}- h)$] and label (2) denotes floodplain bed(s) with length ($\tilde{B}-b$). Label (3) denotes the two main channel walls and the bed of the main channel is represented by label (4).The measured shear stresses are integrated over the respective lengths of each boundary elements to obtain the boundary shear force per unit length for the elements. The total shear force carried by the floodplain beds and walls are very important because the apparent shear force acting on the assumed interfaces originating from the junction between floodplain and main channel can be determined once this quantity is known.

The sum of the boundary shear forces for all beds and walls of the compound channel is used as a divisor to calculate the shear force percentages carried by the boundary elements. The shear force percentage carried by the floodplains is represented as $\%S_f$, and for the main channel it is represented as $\%S_m$. The shear force percentages carried by the floodplain ($\%S_f$) with depth ratio $(H–h)/H$ for all of the compound channels for varying geometries (α = 2.13–5.25) are given in Col.11 of Table 1. It can be seen from Table 1 that the value of flood plain shear increases with depth of flow in the compound channel. This follows the established theory.

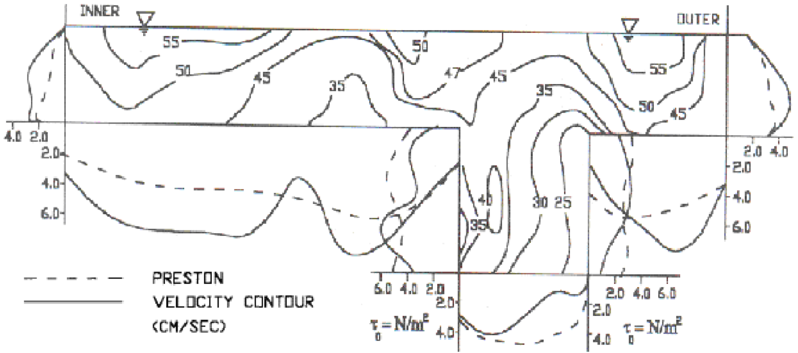


FIG. 2 (a) Isovel and Boundary shear stress distribution of Meandering Channel with both side Flood plain

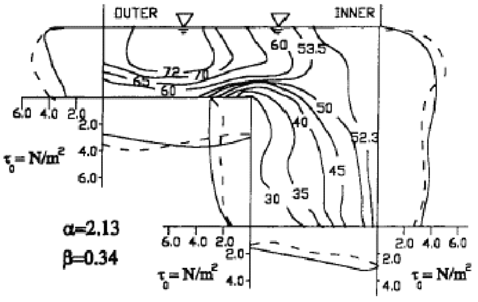


FIG. 2(b) Isovel and Boundary shear stress distribution of Meandering Channel with one side Flood plain

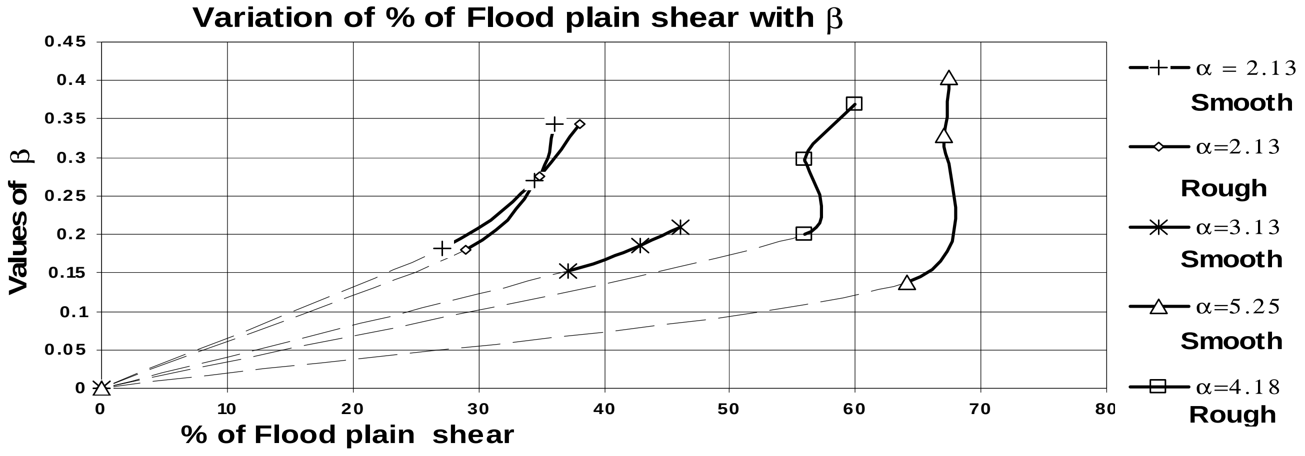


FIG. 3 Variation % of Flood plain shear with Relative depth

For the meandering compound channels, the variation of shear force in floodplains with relative depth $\beta[= (H - h)/H]$ for different values of α $[=B/b]$ are shown in Fig.3.The figure indicates that the percentage of total shear force carried by the floodplain beds and walls $\%S_f$ for meandering compound channel increases with increase in, relative depth β, the channel width ratio α and sinuosity S_r .

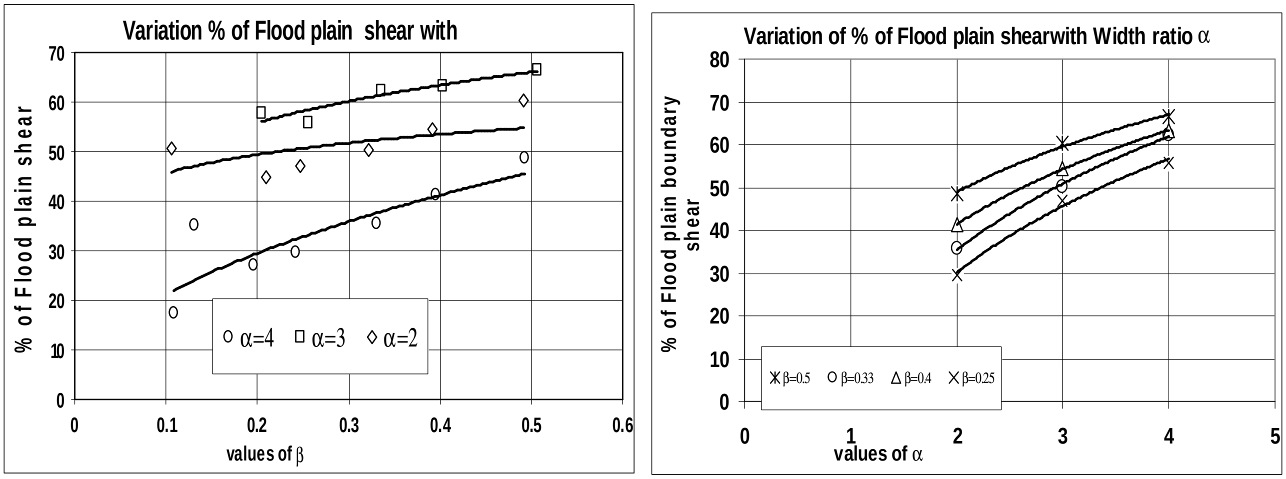


Fig 4(a) **Fig. 4 (b)**

Fig. 4 Variation of Flood plain shear with Depth Ratio β and Width Ratio α

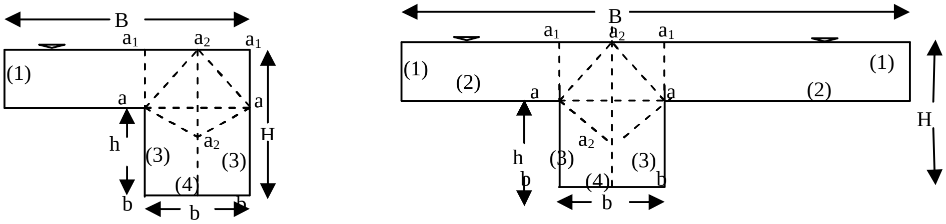
The variation of floodplain shear for straight compound channel of Knight and Demetriou(1983) has been plotted in fig.4. It can clearly be noted from Fig.4(a) that the percentage of floodplain shear (%S_f) increases with β for various compound channel geometry ($\alpha = 2$, $\alpha = 3$, $\alpha = 4$) and from Fig 4(b) it is also observed that percentage of floodplain shear (%S_f) also increases with increase in value of α for constant value of β.

APPARENT SHEAR FORCE ON VARIOUS INTERFACES

The apparent shear force at the assumed interface plane gives an insight into the magnitude of flow interaction between the main channel and the adjacent floodplains basing on which the merits of the selection of the interface plains for discharge estimation are decided. The conventional method of calculation of discharge in compound sections divides the channel into hydraulically homogeneous regions by plane originating from the junction of the floodplain and main channel, so that the floodplain region can be considered as moving separately from the main channel. The assumed plane may be: (1) Vertical interface aa_1; (2) horizontal interface aa or (3) diagonal interface aa_2 (Fig.5)**.** Once the shear force carried by the floodplain is known, the apparent shear force acting on the imaginary interface of the compound section can be calculated. These apparent shear forces may then be used to get an idea of the momentum transfer between the different subsections of the compound channel. For any regular prismatic channel under uniform flow conditions the sum of boundary shear forces acting on the main channel wall and bed together with an ‘‘apparent shear force’’ acting on the interface plane between main channel and floodplain must be equal to the resolved weight force along the main channel given as.

$$\rho g A_{mc} S = \int_{mc} \tau dp + ASF_{ip} \qquad (1)$$

in which g = gravitational acceleration, ρ= density of flowing fluid, S = slope of the energy line, A_{mc} = area of the main channel defined by the interface plane, $\int_{mc} \tau dp$ = shear force on the surfaces of the main channel consisting of two vertical walls and bed, and ASF_{ip} = apparent shear force of the imaginary interface plane. Because the boundary shear stress carried by the compound section ($\rho g A S$) is equal to 100%, where A is the total cross section of the compound channel, the percentage shear force carried by the main channel surfaces can be calculated as



Compound Channel with one side floodplain

Compound Channel with floodplain on both sides

Fig. 5 Notations

$$\% S_{mc} = 100\,\frac{\int_{mc} \tau\, dp}{\rho gAS} = 100\,\frac{\rho g A_{mc} S}{\rho gAS} - 100\,\frac{ASF_{ip}}{\rho gAS} \tag{2}$$

But since $\%S_m = 100 - \%S_f$; and $100(ASF_{ip}/\rho gAS)$ = percentage of shear force on the assumed interface, substituting the values the apparent shear force on the interface plane is calculated as

$$\% ASF_{ip} = 100\,\frac{A_{mc}}{A} - \{100 - \% Sf\} \tag{3}$$

in which $\%ASF_{ip}$ = percentage of shear force in the interface plane. These apparent shear forces can be expressed as percentages of the total channel shear force using the following relations:

$$\% ASF_V = \frac{50}{[(\alpha - 1)\beta + 1]} - \frac{1}{2}\{100 - \% Sf\} \tag{4a}$$

$$\% ASF_D = \frac{25(2-\beta)}{[(\alpha - 1)\beta + 1]} - \frac{1}{2}\{100 - \% Sf\} \tag{4b}$$

$$\% ASF_H = \frac{100(1-\beta)}{[(\alpha - 1)\beta + 1]} - \{100 - \% Sf\} \tag{4c}$$

Percentages of apparent shear force for the assumed vertical, horizontal, and diagonal interface planes may be calculated using (4). For example, for vertical interface between the boundary of the floodplain and main channel shown as the lines aa_1 in Fig.5 the value of A_{mc} is the area marked by a_1abbaa_1, which when substituted in (4), yields $\%ASF_V$. Similarly, for horizontal or diagonal interfaces, A_{mc} can be estimated from the areas marked as aabb or $a_2aabbaa_2$, respectively, in Fig.5. Selection of suitable interfaces for calculating conveyance by divided channel method becomes easier once we know the apparent shear in different assumed interfaces. Toebes and Sooky (1967) carried out laboratory experiments on two stage meandering composite channel section and showed that a nearly horizontal fluid boundary located at the junction between the main channel and flood plain would be more realistic than other interfaces. Wormleaton, et al. (1980, 1982) have proposed an (apparent shear stress ratio from the apparent shear by which a suitability of interface plain for calculation of discharge can be predicted. Patra and Kar (2000) have proposed the variable interface method of discharge calculation for meandering and straight compound channel. Holden (1986), Stephenson and Kolovpoulos (1990) proposed the area method for discharge calculation in compound channel by selecting a curved interface by assuming the apparent shear along the interface length as zero.

For the assumed vertical interface plane the shear force is always positive for the ranges of α and β tested. A positive value indicates transfer of momentum from the main channel to the floodplain at the assumed plane indicating the floodplain flow retarding the main channel flow. This apparent shear stress is higher than the bed-shear stress at low floodplain depths and reduces gradually as β increases. For example, for channel series A.1 the apparent shear stress is 4.2% per unit length of the vertical interface plane while the bed shear stress of the main channel per unit length of wetted perimeter is 1.2% of the total shear stress. This follows a similar trend for all other channels runs. For the diagonal and horizontal interface planes it is observed that the apparent shear force is positive at low depths and changes sign as depth increases indicating that at higher depths over floodplain there is transfer of momentum from the floodplain to the main channel. A smaller value of apparent shear stress renders the interface plane more suitable, but a large negative value of apparent shear stress at higher depths makes the interface plane unsuitable for separating the channel into hydraulically homogeneous zones for calculating discharge of compound channels by the divided channel method.

DEVELOPMENT OF THE MODEL

Knight and Hamed (1984) investigated smooth compound channels having a bank full depth of 76 mm that can be considered close to the present channels for which most of data are presented and proposed equation for the percentage of total shear force carried by the floodplain as

$$\%S_f = 48(\alpha - 0.8)^{0.289}(2\beta)^m \tag{5a}$$

where the exponent m can be calculated from the relation $m = 1/\left[0.75\,e^{0.38(\alpha - R)}\right]$. These equations apply to the straight compound channels having symmetry with respect to the main channel centerline. Patra and Kar (2000) proposed equation for calculating the percentage of total shear force carried by the floodplain for the meandering compound channels as

$$\%S_f = 48(\alpha - 0.8)^{0.289}(2\beta)^m\left[1 + \alpha\,\mathrm{Re}^{-13.25\beta\delta}\right] \tag{5b}$$

in which R = ratio of the amplitude of the meandering channel to the top width B of the compound section, the values of which are given in col. 9 of Table 1, and δ = aspect ratio of the main channel b/h. The equation is valid for the meandering compound sections for smooth boundaries or with same roughness in the floodplain and in the main channel. For the compound channel with different roughness Patra and Kar (2000) further proposed the following general equation for the percentage of floodplain shear as

$$\%S_f = 48(\alpha - 0.8)^{0.289}(2\beta)^m[1 + \alpha\,\mathrm{Re}^{-13.25\beta\delta}]\{1 + 1.02\sqrt{\beta}\log\gamma\} \tag{5c}$$

where γ = the ratio of Manning's roughness n of the floodplain to that for the main channel. For straight channel the value of R is zero. A zero value of R reduces (5*c*) to the form of (5b) and for channels with equal surface roughness in the floodplain and main channel for $\gamma = 1$, the equation further reduces to the form proposed by Knight and Hamed (1984).

Due to complexity of the empirical equations proposed by the previous investigators a regression analysis is made to obtain a simple but more reliable equation to predict the percentage of floodplain shear. From these plots between ($\%S_{fp}$) with ($\%S_{fp}$) for the straight compound channel of Knight & Demetriou(1983) and for the meandering compound channel of Patra & Kar(2000) the best fitted simple linear function. is obtained and for a straight compound channel the equation for percentage of shear carried by floodplain is modeled as

$$\%S_f = 0.822\,\%A_f + 19.587 \tag{6a}$$

Or

$$\%S_f = 0.822\,\frac{\beta(\alpha - 1)}{1 + \beta(\alpha - 1)} + 19.6 \tag{6b}$$

Equation (6) is valid for straight compound channel with smooth surfaces only. For different roughness in main channel and flood plain surface, Equation (6) is further improved and is represented as.

$$\%S_f = \left(0.822\,\frac{\beta(\alpha-1)}{1+\beta(\alpha-1)}+19.6\right)\{1+1.02\sqrt{\beta}\,\log\gamma\} \qquad (7)$$

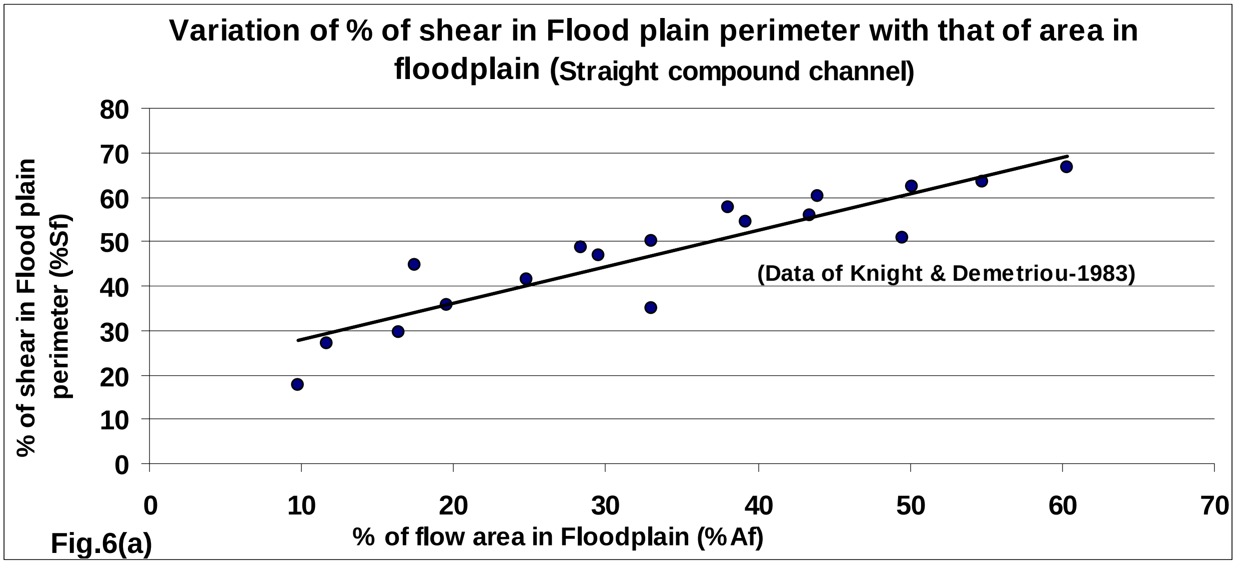


Fig. 6(a) Variation of % of shear in Flood plain perimeter with that of area in floodplain (Straight compound channel)

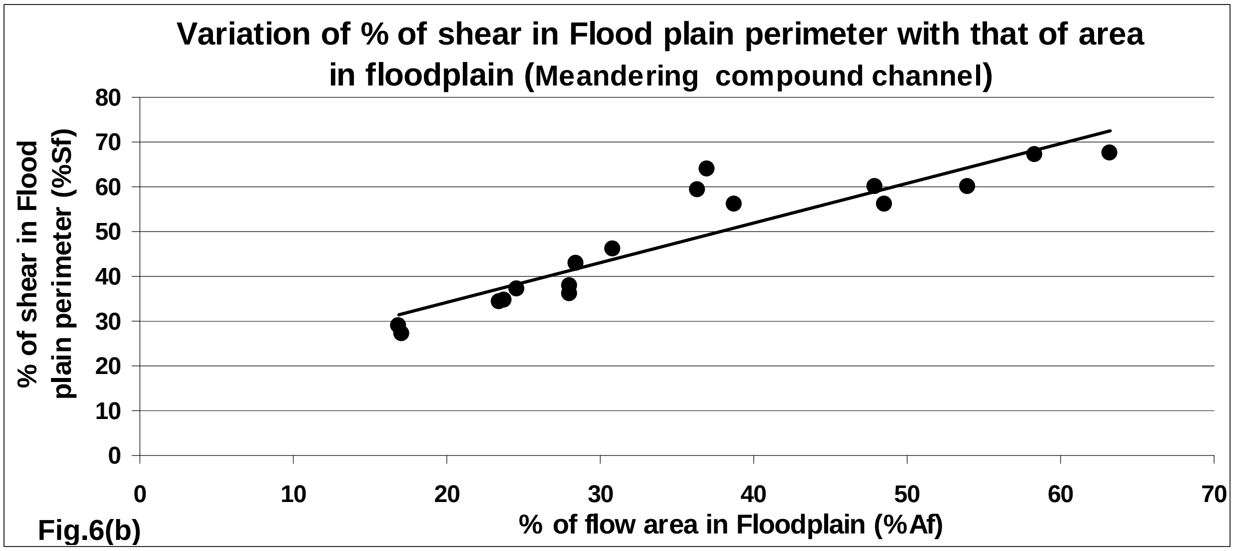


Fig. 6(b) Variation of % of shear in Flood plain perimeter with that of area in floodplain (Meandering compound channel)

where γ = the ratio of Manning's roughness n of the floodplain and that for the main channel. For meandering channel with floodplain the distribution is further complicated and modified due to meandering effect. It has been observed from the experimental result that the percentage of boundary shear is exponentially on amplitude/width ratio = R. Finally a general model to represent the %S of shear force carried by floodplain of meandering compound channel is given as

$$\%S_f = \left(0.822 \frac{\beta(\alpha - 1)}{1 + \beta(\alpha - 1)} + 19.6 \right) \left(1 + \alpha \, \mathrm{Re}^{-13.25\beta\delta}\right) \{1 + 1.02\sqrt{\beta} \log \gamma\} \tag{8}$$

Review of the literature show that investigators propose alternatives interface planes to calculate the total discharge carried by a compound channel section. Either including or excluding the interface length in the wetted perimeter does not make sufficient allowance for discharge calculation for all depths of flow over floodplain. It either overestimates or underestimates of the discharge results because of not taking care of momentum transfer in terms of apparent shear at the respective interfaces. Having computed $\%S_f$ through (8), it is easy to evaluate (4) for the assumed interface plane. After finding out apparent shear in the assumed interface of a compound channel, it becomes easier for selection of suitable interfaces for discharge calculation. While calculating the discharge of the compound channel using divided channel method the apparent shear is found to be negligible for any interfaces for a particular depth of flow, than for the sub-section perimeter the interface length is not included for discharge calculation. After finding the sub section discharges the total section discharge is obtained by adding the sub section discharges. For any depth of flow in a compound channel if apparent shear is equal to boundary shear of main channel or flood plain than the interface lengths are added to the subsection perimeter of main channel to obtain the correct discharge. If apparent shear is very large compared to boundary shear of the subsection perimeter for any over bank depth of flow than the selection of respective interface plain gives erroneous discharge result by using the simple divided channel method. For these cases by simply including or excluding the interface lengths in the subsection wetted perimeter for discharge calculation do not justify the amount of momentum transfer in the respective interfaces of the over bank flow.

Using(8) the value of percentage of flood plain shear($\%S_f$) are calculated. The variation of computed percentage of shear force of floodplain wetted perimeter with the observed value of the straight compound channels of Knight and Demetrious (1983) is shown in Fig. 7(a). The variation of computed percentage of shear force of flood plain wetted perimeter with the observed value for meandering compound channels of Patra and Kar (2000) is plotted in Fig. 7(b). Fig. 7 shows the adequacy of the equation(8).

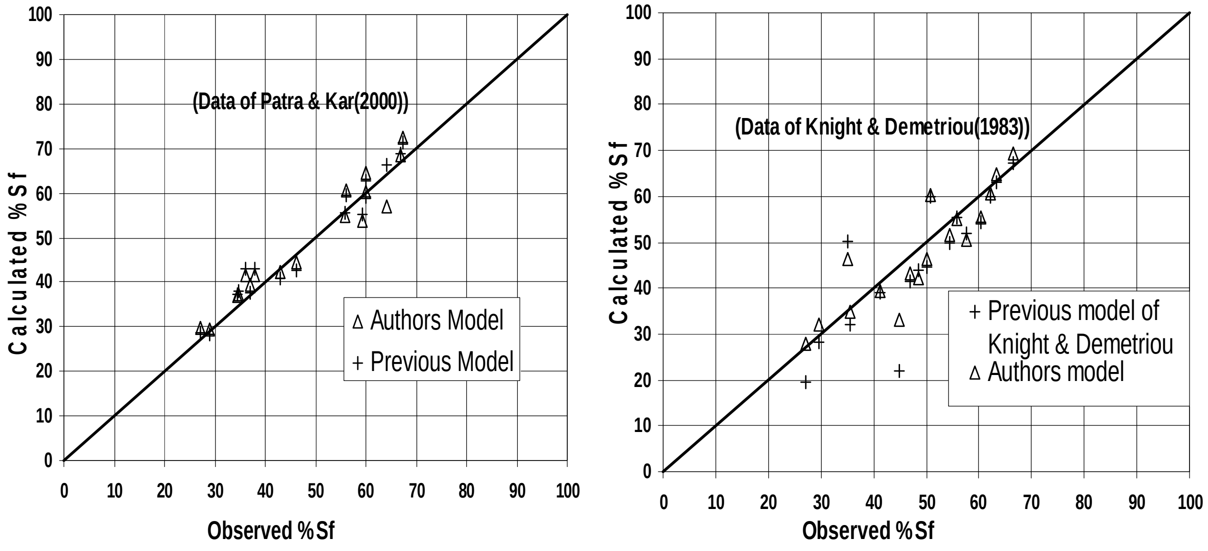


Fig. 7(a) **Fig. 7(b)**

Fig. 7 Variation of Observed Value and Modeled Value of Flood plain shear

CONCLUSIONS

The following conclusions are drawn:

1. The distribution of boundary shear along the perimeter of straight and meandering compound channels is examined and an empirical relationship to predict boundary shear distribution for the types of geometry is proposed.
2. For the meandering compound channels the important parameters effecting the boundary shear distribution are sinuosity (S_r), the amplitude (ε), relative depth (β) and the width ratio (α) and the aspect ratio (δ). These five dimensionless parameters are used to form general equations representing the total shear force percentage carried by floodplains.
3. The proposed equations give good result with the observed data for the straight compound channel of Knight and Demetrious (1983) as well as for the meandering compound channels. The models is found to be quite adequate in defining the relation ship for $\%S_f$

It is recommended that further investigation be focused on extending the present analysis to the compound channel of different cross sections such as trapezoidal cross sections.

NOTATIONS

The following symbols are used in this paper

A = total cross-sectional area of compound channel;
B = top width of compound channel;
b = width of main channel;
g = gravitational acceleration;
H = depth of flow in main channel;
h = height of main channel up to floodplain bed;
m = exponent used in Eq. (6b);
n = Manning's roughness factor;
n_1= exponent used in Eq. (5b);
R = ratio of amplitude of compound channel to top width B;
S_r = sinuosity of meander channel

α= width ratio = B/b;
β = relative depth = $(\tilde{H} - h)/H$;
γ= ratio of floodplain roughness to main channel roughness;
δ= ratio between main channel width to its depth (b/h);
ρ = density of flowing liquid;
τ= boundary shear stress;
$\int_{mc} \tau dp$ = shear force on surfaces of main channel;
%ASF = percentage of total channel shear force carried by assumed interface planes;
%ASF_H = ASF on horizontal interface (aa) as percentage of total shear force;
%ASF_{ip} = ASF on an interface plane as percentage of total shear force;
%ASF_V = ASF on vertical interface (aa1) as percentage of total shear force;
A_{mc} = are the area of main channel
A_{fp} =flood plain subsections respectively,
τ_{mc} = the mean boundary shear stress in main channel per unit length longitudinally
τ_{fp} = mean boundary shear stress in flood plain per unit length longitudinally
S = the longitudinal slope of the channel.
% S_f= the percentage of shear force carried by the floodplains
%S_m= the percentage of shear force carried by the floodplains

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