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APPARENT SHEAR STRESS IN A COMPOUND CHANNEL

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ABSTRACT

The flow structure of a compound channel is a complicated process due to the transfer of momentum between the deep main channel and the adjoining shallow floodplains. Experiments are carried out to measure the boundary shear around the wetted perimeter of a two-stage compound channel and to quantify the momentum transfer in terms of apparent shear stress along the assumed interfaces originating from the junction between main channel and flood plain. This is further helpful for deciding appropriate interface plains for evaluation of accurate stage-discharge relationship for a compound channel of all geometry. The lateral momentum transfers are found to magnificently affect the shear stress distribution in flood plain and main channel sub sections. Knowledge of momentum transfer to different interfaces can be acquired from the distribution of boundary shear in the sub sections. In the present work, commonly used equations of shear stress distributions across assumed interface plane are analyzed and tested for various types of compound channels and their flow conditions using published data. Furthermore, a modified expression to predict the boundary shear distribution in compound channels that is good for all width ratios is derived and is found to provide significant improved results. The model are also validated using the well published data.

Key words: Apparent Shear, Boundary Shear, Interface Plane, Compound Channel, Flood Plain, Main Channel, Over-bank Flow, Momentum Transfer.

INTRODUCTION

During floods, a part of the river discharge is carried by the main channel and the rest is 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 the momentum transfer between them. The momentum transfer in a compound channel was first investigated and demonstrated by Sellin [1964] and Zheleznvakov [1965]. They indicated the presence of artificial banks made of vortices at the junction region, which acts as a medium for lateral momentum transfer. Furthermore, many investigators found that the momentum transfer is responsible for the non-uniformity in the boundary shear stress distribution across the section perimeter (e.g., Ghosh and Jena [1971], Rajaratnam and Ahmadi [1979], Knight and Hamed [1984], Myers, W.R.C., & Elsawy [1975], Patra& Kar [2000], Patra & Khatua [2006]. At low depths of flow over floodplain, transfer of momentum takes place from the main channel flow to the floodplain leading to the decrease in the main channel velocity and discharge, while its floodplain components are increased. At higher depths over floodplains the process of momentum transfer reverses, the floodplain supplies momentum to the main channel. Many investigators have shown that, the interaction mechanism causes the differential boundary shear distribution in the sub-section perimeter of a compound channel (e.g (e.g., Ghosh and Jena [1971], Rajaratnam and Ahmadi [1979], Knight and Hamed [1984], Myers, W.R.C., & Elsawy[1975], Patra& Kar [200], Patra & Khatua [2006]).

Information regarding the nature of boundary shear stress distribution in a flowing simple and compound channel 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, to design stable channels, revetments. 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. Due to momentum transfer, the distribution of boundary shear is more complex in a compound channel than that for a channel of simple geometry. The interaction mechanism in a compound channel has the effect of increasing floodplain shear and decreasing main channel shear (e.g.,[Rajaratnam and Ahmadi [1979], Myers, W.R.C. & Elsawy[1975]). Because of interaction effect between the sub-section flows there is wide variation in the local shear stress distribution from point to point in the wetted perimeter of a compound channel. Therefore, there is a need to evaluate the boundary shear stress carried by the main channel and floodplain perimeters at various locations. The velocity distribution and boundary shear stress distribution in compound cross section channels have also been investigated by many authors (e.g., Ghosh and Jena [1971], Rajaratnam and Ahmadi [1979], Myers, W.R.C., & Elsawy [1975], Patra& Kar [2000], Khatua [2008]).Knowledge of momentum transfer or the knowledge of boundary shear stress distribution are also helpful to predict the stage-discharge relationship of a compound channel.

The traditional discharge predictive methods for compound channels either use the Single-Channel Method (*SCM*) or the Divided-Channel Method (*DCM*). The *DCM* divides a compound section into hydraulically homogeneous sub-sections generally by vertical, inclined or horizontal division lines that lead to an averaged flow velocity for each sub-section (e.g., Chow [1959]). These approaches have the advantage of recognizing the particular hydraulic properties in the respective compartments. Therefore, this method predicts better overall discharge as compared to SCM (Weber and Menéndez [2004], and Patra and Khatua [2006]) but it overestimates the flow in main channel and underestimates the flow in the floodplain, due to neglect of lateral momentum transfer. The *DCM* is extensively used because of its simplicity and is still the primary tool used by engineers for modeling stage-discharge relations in compound channels. For example, the treatment of lateral variability in commercial software tools for one-dimensional river modeling such as the *SOBEK, MIKE11*; and *HEC-RAS* are all based on *DCM*. From the knowledge of lateral momentum transfer, various investigators have proved the adequacy of proper selection of interface plains using *DCM* for evaluation of stage-discharge relationship in a compound channel (e.g., Ackers [1992], Wright and Carstens [1970], Wormleaton et al. [1982], Mohaghegh and Kouchakzadeh [2008] Seckin [2004], Patra et al. [2004] Kejun Yang et al.[2007], Prinos and Townsend [1984], Christodoulou [1992], Patra and Khatua [2006] and Huttof et al. [2008]) etc. Keeping the above facts in view, an attempt has been made to analyse the momentum transfer which is further helpful to select an appropriate interface plain for *DCM*. The present paper is also directed to study the information on boundary shear distribution basing on which models on momentum transfer and stage-discharge relationship of compound channels for narrow as well as very wide floodplains can be developed.

EXPERIMENTAL ANALYSES

In the present work, the compound channel is constructed from Perspex sheets in the Hydraulic Engineering Laboratory of the Civil Engineering Department, National Institute of Technology, Rourkela, India. The compound channel is symmetrical about the centerline of main channel making the total width of the compound section as 440 mm (Figure 1). The main channel is rectangular in cross section having 120 mm width and 120 mm at bank full depth. Longitudinal bed slope of the channel is taken as 0.0019. The roughness of the floodplain and main channel are identical. The bed roughness coefficient (Manning coefficient *n*) is estimated to be 0.01 from experiments in the channel.

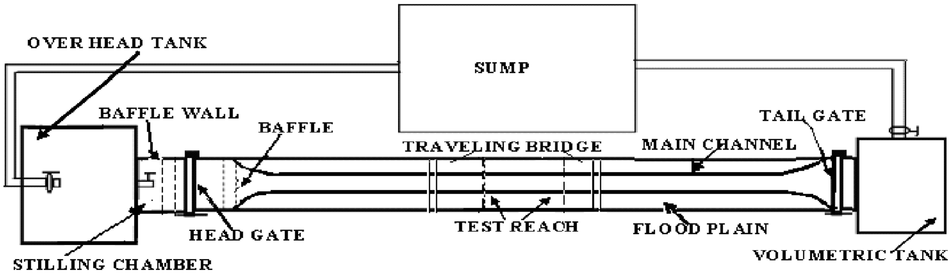

Figure 1 (a) Plan view of experimental set up of the compound channel

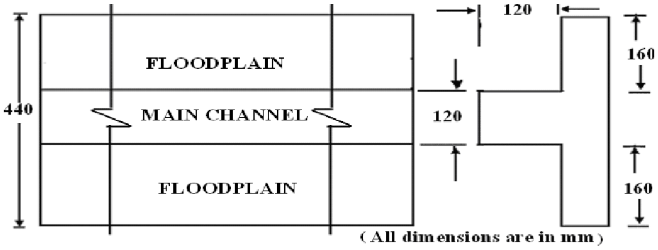

Figure 1(b) Definition sketch of the compound channel

A re-circulating system of water supply is established with pumping of water from an underground sump to an overhead tank from where water flows under gravity to the experimental channel through stilling chamber and baffle wall. A transition zone between stilling tank and the channel reduces turbulence of the flow water. 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 volumetric tank that helps to measure the discharge rate. From the volumetric tank water runs back to the underground sump**.**

The measuring devices consist of a point gauge mounted on a traversing mechanism to measure flow depths with least count of 0.1 mm. Point velocities are measured at a number of locations across the channel section using a 16-Mhz Micro *ADV* (Acoustic Doppler Velocity-meter) having accuracy of 1% of the measured range. A guide rail is provided at the top of the experimental flume on which a traveling bridge is moved in the longitudinal direction of the entire channel. The point gauge and the micro-*ADV* attached to the traveling bridge can move both longitudinal and the transverse direction at the bridge position. Readings from the micro-*ADV* are recorded in a computer. As the *ADV* (down probe) is unable to read the data up to 50 mm from free surface, a micro-Pitot tube of 4 mm external diameter in conjunction with suitable inclined manometer are also used to measure velocity at some other points of the flow-grid. The Pitot tube is physically rotated with respect to the main stream direction till it gives maximum deflection of the manometer reading. A flow direction finder having a least count of 0.1^o is used to get the direction of maximum velocity with respect to the longitudinal flow direction. The angle of limb of Pitot tube with longitudinal direction of the channel is noted by the circular scale and pointer arrangement attached to the flow direction meter. The overall discharge obtained from integrating the longitudinal velocity plot and from volumetric tank collection is found to be within ±3% of the values. Using the velocity data, the boundary shear at various points on the channel beds and walls are evaluated from a semi log plot of velocity distribution. Boundary shear stresses are also obtained from the manometric readings of the head differences of Preston tube techniques using Patel's [1965] relationship. Error adjustments to the shear value are done by comparing the corresponding shear values obtained from the energy gradient approach. The results so obtained by the two methods are found to be consistently within ±3% values.

Table 1 Details of geometrical parameters of the experimental compound channel and other applied channels

Verified test channel	Series No.	Longitudinal slope (*S*)	Main channel Width (*b*) in mm	Main channel depth (*h*) in mm	Main channel side slope (*s*)	Ratio of Manning's roughness coefficients ($\gamma = n_{fp}/n_{mc}$)	Width ratio (α)	Observed discharge (*Q*) range in cm^3/s	Relative depth (β) ranges = *(H-h)/H*
Present Channel	Type-I	0.0019	120	120	0	1	*B/b* = 3.667	8726-39071	0.118- 0.461
Knight & Demetriou [13]	01	0.00096	304	76	0	1	*B/b* =2	5200-17100	0.108-0.409
	02	0.00096	456	76	0	1	*B/b* =3	5000-23400	0.131-0.491
	03	0.00096	608	76	0	1	*B/b* =4	4900-29400	0.106-0.506
FCF Series-A channels	01	1.027×10 -3	1500	150	1.0	1	*B/b*=6.67	208200-1014500	0.056-0.400
	02	1.027×10 -3	1500	150	1.0	1	*B/b*=4.2	212300-1114200	0.0414-0.479
	03	1.027×10 -3	1500	150	1.0	1	*B/b*=2.2	225100-834900	0.0506-0.500
	08	1.027×10 -3	1500	150	0	1	$2b_{fp}/b = 3.0$	185800-1103400	0.0504-0.499
	10	1.027×10 -3	1500	150	2.0	1	$2b_{fp}/b = 3.0$	236800-1093900	0.0508-0.464

EXPERIMENTAL RESULTS CONCERNING VELOCITY AND BOUNDARY SHEAR

The stage discharge relationship for the present experimental compound channel from in-bank to over-bank flow conditions are shown in Fig.2. A total 21 numbers of stage-discharge data for both in-bank and over-bank flow conditions are observed at the test reach and the summary is given in Table 1. Out of the 10 over-bank stages discharge data, detailed velocity measurements for 5 stages (i.e. runs S13, S15, S17, S18, S19 as shown in Table.1) are recorded at number of points at the pre defined grid points. Various boundary elements of the compound channel comprising the wetted parameters are labeled as (1), (2), (3) and (4) as shown in Fig. 4. Label (1) denotes the vertical wall(s) of floodplain of length $[2(H – h)]$, and (2) denotes floodplain beds of length $(B – b)$. Label (3) denotes the two main channel walls of length $(2h)$ and the bed of the main channel of length b is represented by label (4). Experimental shear stress distributions at each point of the wetted perimeter are numerically integrated over the respective sub-lengths of each boundary element (1), (2), (3), and (4) to obtain the respective boundary shear force per unit length for each element. Sum of the boundary shear forces for all the beds and walls of the compound channel is used as a divisor to calculate the shear force percentages carried by the boundary elements. Percentage of shear force carried by floodplains comprising elements (1) and (2) is represented as ($\%S_{fp}$) and for the main channel [(3) + (4)], it can be taken as ($\%S_{mc}$). The lumped effect of momentum transfer between the main channel and floodplain, the surface resistance, and other flow properties are manifested in the form of boundary shear distribution at the walls and beds of the channel section. The velocity and boundary shear stress distribution for two run of the experimental channels (S_{15} and S_{18}) are shown in Figure 3a and 3b. Summary of the discharges and percentage of boundary shear in the floodplain ($\%S_{fp}$) for different relative depths (β) observed from the experimental runs are given in Table 2.

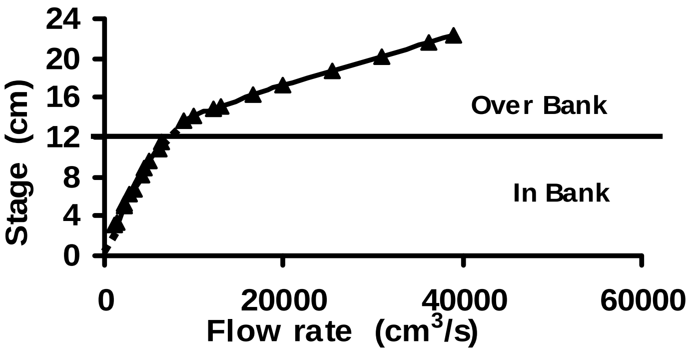

Fig.2 Stage discharge relationships for the experimental compound channel

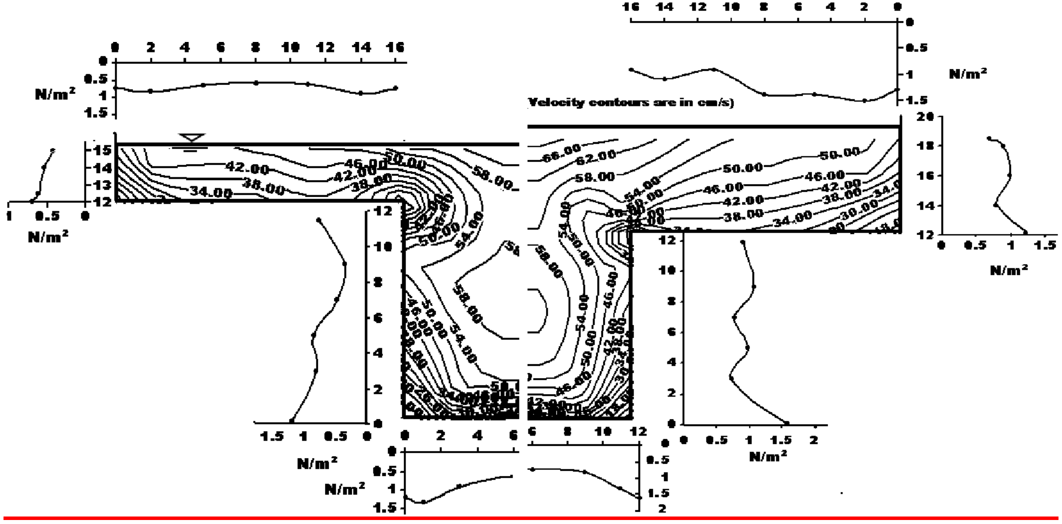

Fig. 3 a, b Velocity and boundary shear distribution for runs S_{15} and S_{18} of the experimental channel for flow depths H = 15.15 cm and 18.75 cm respectively

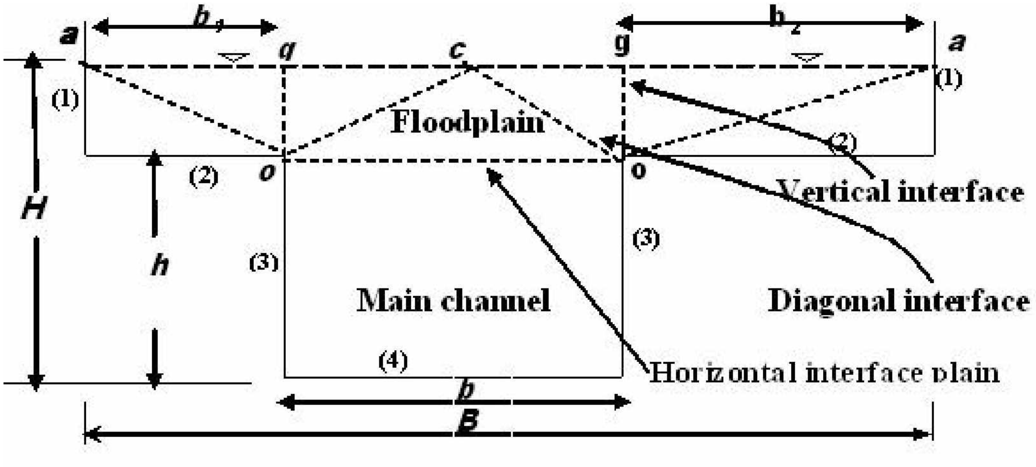

Figure 4 Interface Planes dividing a compound section into sub areas

Table 2 Summary of flow parameters, boundary shear distribution and apparent shear stress results for the experimental compound channel flow

Run No	Flow Dept h (cm)	Discharg (cm^3/sec	Relative depth (ß)	Overall Mean shear (N/m2)	Observ ed (% S_{fp})	Computed (% S_{fp}) using eq.11	%ASF_v	% ASF_D	%ASF_H
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
S12	13.62	8726	0.12	0.56	*	39.39	*	*	*
S13	14.12	10007	0.15	0.61	42.10	43.11	6.75	2.78	4.07
S14	14.88	12245	0.19	0.68	*	47.58	*	*	*
S15	15.15	13004	0.21	0.71	47.64	48.92	5.99	-1.40	2.64
S16	16.32	16706	0.26	0.81	*	53.61	*	*	*
S17	17.25	19861	0.30	0.89	53.70	56.43	5.45	-7.90	0.25
S18	18.75	25329	0.36	1.00	59.70	59.86	5.36	-7.65	0.77
S19	20.21	30844	0.41	1.11	61.10	62.34	4.55	-10.40	-0.32
S20	21.62	36275	0.44	1.21	*	64.21	*	*	*
S21	22.28	39071	0.46	1.26	*	64.95	*	*	*

***Measurement of point velocities, calculation of (%S_{fp}) and the percentages of apparent shear are not performed for these runs.**

METHODOLOGY

Boundary Shear Distribution

Knight and Demetriou [1983], and Knight and Hamed [1984] proposed an equation for (%S_{fp}) for a compound channel section as

$$\% S_{fp} = 48(\alpha - 0.8)^{0.289}(2\beta)^{m} \qquad (1)$$

Equation (5) is applicable for the channels having equal surface roughness in the floodplain and main channel. For non-homogeneous roughness channels the equation is

$$\% S_{fp} = 48(\alpha - 0.8)^{0.289}(2\beta)^{m}\{1 + 1.02\sqrt{\beta}\log\gamma\} \qquad (2)$$

in which, α = Width ratio = B/b , β = relative depth =$(H - h)/H$, γ = the ratio of Manning's roughness n of the floodplain to that for the main channel, b= width of main channel, B = total width of compound channel, h = bank full depth and H = total depth of flow . The exponent m can be evaluated from the relation

$$m = 1/\left\lfloor 0.75e^{0.38\alpha} \right\rfloor \qquad (3)$$

For homogeneous roughness section (γ =1), equation (2) reduces to the form of Knight and Hamed [1984] i.e. equation (1). Due to complexity of the empirical equations proposed by the previous investigators a regression analysis is also made by Khatua and Patra [2007] and proposed an equation for (%S_{fp}) as

$$\% S_{fp} = 1.23\,\beta^{0.1833}\,(38\,Ln\,\alpha + 3.6262)\,\{1 + 1.02\sqrt{\beta}\,\log\gamma\} \qquad (4)$$

Apparent Shear Force across the Assumed Interface Planes

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. 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.

For any regular prismatic channel under uniform flow conditions, the sum of boundary shear forces acting on the main channel wall and bed, along 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. It can be expressed as

$$\rho g A_{mc} S = \int_{mc} \tau dp + ASF_{ip} \qquad (5)$$

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, A= total cross section of the compound channel $\int_{mc} \tau dp$= 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 (ρgAS) is equal to 100%, the percentage shear force carried by the main channel surfaces can be calculated as

$$\% S_{mc} = 100 \frac{\int_{mc} \tau \, dp}{\rho gAS} = 100 \frac{\rho g A_{mc} S}{\rho gAS} - 100 \frac{ASF_{ip}}{\rho gAS} \qquad (6)$$

But since $\% S_{mc} = 100 - \% S_{fp}$; 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 can be calculated as

$$\% ASF_{ip} = 100 \frac{A_{mc}}{A} - \{100 - \% S_{fp}\} \qquad (7)$$

in which $\% ASF_{ip}$ = percentage of shear force in the interface plane. Having computed ($\% S_{fp}$) using equation (1), it is easy to evaluate equation (6) for the assumed interface plane. The momentum transfer from the main channel to flood-plain is considered as positive percentages of apparent shear and that from flood-plain to main channel is taken as negative. From experiments it is seen that apparent shear stress is higher than the bed-shear stress at low floodplain depths and reduces gradually as over-bank flow depth increases (Rajaratnam and Ahmadi [1979], Myers and Elsawy [1975], Knight and Demetriou[1983], Patra and Khatua[2006]). 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 Divided Channel Method (*DCM)*.

For example, the percentages of apparent shear ($\% ASF_V$) for vertical interface (*og*) in Figure 3 is obtained by putting $\theta = 0^{o}$, in (12) as

$$\% ASF_V = \frac{50}{[(\alpha - 1)\beta + 1]} - \frac{1}{2}\{100 - \% S_{fp}\} \qquad (8a)$$

Similarly the percentages of apparent shear for horizontal interface can be obtained by considering $\theta = 90^{o}$ in (12) as

$$\% ASF_H = \frac{100(1-\beta)}{[(\alpha - 1)\beta + 1]} - \{100 - \% S_{fp}\} \qquad (8b)$$

And for diagonal interface ($\% ASF_D$) is obtained by considering $\tan\theta = b/2h$ in (12) or (13) as

$$\% ASF_D = \frac{25(2-\beta)}{[(\alpha - 1)\beta + 1]} - \frac{1}{2}\{100 - \% S_{fp}\} \qquad (8c)$$

In Figure 4, the vertical, horizontal, and diagonal plains of separation of the compound channel are represented by the interface lengths *o-q*, *o-o*, and *o-c* respectively. The analysis of momentum transfer helps in prediction of stage-discharge relationship of a compound channel, which is discussed in the later part of the paper. Further the knowledge of the apparent shear is useful to choose appropriate sub-division lines for separating a compound channel into sub-sections for accurate discharge assessment using the Divided Channel Method (*DCM*). The conventional method of calculation of discharge in compound sections divides the channel into hydraulically homogeneous regions by assuming interface planes 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.4)**.** 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.

THE MODIFIED APPROACH

It is seen that the momentum transfer at an interface (vertical, horizontal or diagonal) plains using equations (8) depend on the most influencing dimensionless parameters like α, β and ($\%S_{fp}$). It is understood that for a compound river section of a given over-bank flow depth both the parameters α and β are known. The third parameter ($\%S_{fp}$) can be calculated using the equation (1) developed by Knight and Demetriou [1983], and also by equation (2) developed by Khatua & Patra [2007]. Knight and Demetriou[1983] have shown the adequacy of boundary shear stress distribution equation (1) for the compound channels having width ratio of α up to 4. However, Khatua & Patra [2007] have shown the adequacy of α up to 5.25. Interestingly, it is found that when equation (4) was tested for FCF data having $\alpha = 6.67$, significant error of ($\%S_{fp}$) was estimated (around 90% by equation (1) and 71% by equation (4) , shown in figure 5). Details of the experimental arrangements relating to phase *A* to *C* of the *FCF* work are obtained from Myers & Brennan [1990] and Greenhill and Sellin [1993].

Figure 5, illustrates the results obtained using equation (1) and (4) and its comparison with the observed values. The error are found to increases with increase in the value of width ratio α as well as with the increase of relative depth β. Furthermore, equation (1) and (4) estimates unrealistic value of $\%S_{fp}$ i.e. $\%S_{fp} > 100\%$ for a compound channel of $\alpha > 10$. Very wide floodplains ($\alpha > 10$) are generally encountered during high floods in natural channels and it is essential to estimate boundary shear stress distribution on such channels.

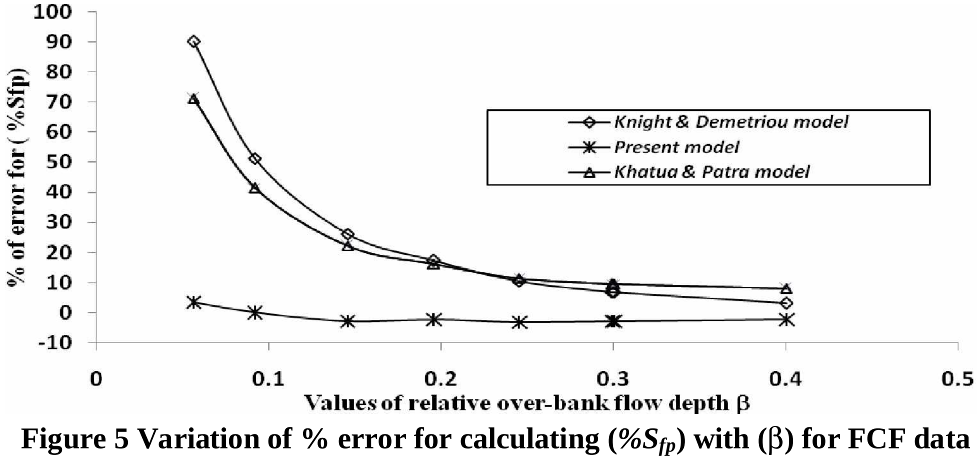

Figure 5 Variation of % error for calculating ($\%S_{fp}$) with (β) for FCF data

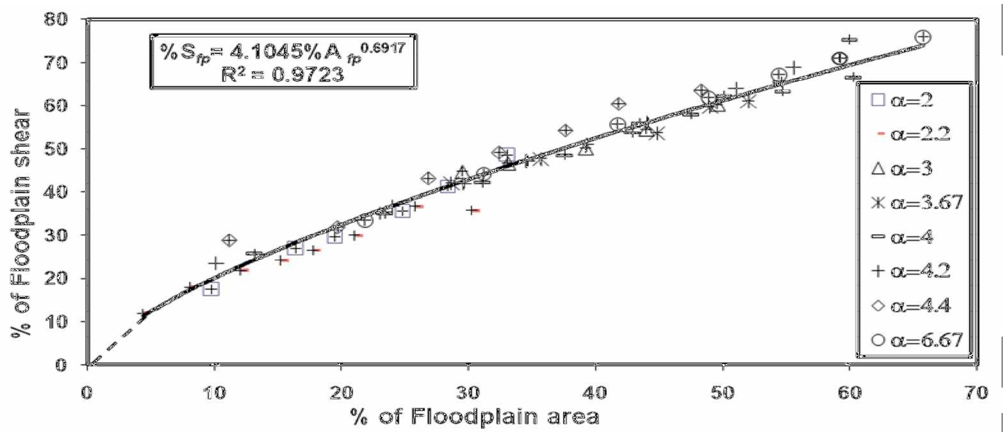

Fig. 6 Variation between percentages of shear in flood plain perimeter ($\%S_{fp}$) and the corresponding flow area ($\%A_{fp}$) for compound channels

To overcome the difficulties, on the basis of 62 overbank flow depth from nine types of compound channels with width ratios ranging from [α =2.0 to 6.67] and the relative depth β ranging from 0.1 to 0.5, the authors have tried to plot the variation of percentages of floodplain area ($\%A_{fp}$) verses ($\%S_{fp}$) as shown in Figure 6. For the variation of ($\%S_{fp}$), the parameter ($\%A_{fp}$) is chosen because, it is a well known fact that boundary shear in open channel flow is directly proportional to the flow area. Of course due to momentum transfer, the distribution of boundary shear (i.e. $\%S_{fp}$) does not follow a linear relationship with that of ($\%A_{fp}$). In the developed approach, the best fit power function for ($\%S_{fp}$) for a compound channel is obtained by plotting ($\%S_{fp}$) and ($\%A_{fp}$). The developed equation given below is a power function equation and the correlation coefficient obtained for the equation is R^2 = 0.98.

$$\%S_{fp} = 4.1045(\%A_{fp})^{0.6917} \qquad (9)$$

By substituting $\frac{A_{fp}}{A} = \frac{\beta(\alpha-1)}{1+(\alpha-1)\beta}$ for a rectangular main channel equation (22) is rewritten as

$$\%S_{fp} = 4.105\left[\frac{100\beta(\alpha-1)}{1+\beta(\alpha-1)}\right]^{0.6917} \qquad (10)$$

Now, the equation (10) can be used for the channels having equal surface roughness in the floodplain and main channel. Following the equation (1) or (4) for non-homogeneous roughness channels (10) can further be modified as

$$\%S_{fp} = 4.105\left[\frac{100\beta(\alpha-1)}{1+\beta(\alpha-1)}\right]^{0.6917}\{1+1.02\sqrt{\beta}\log\gamma\} \qquad (11)$$

DISCUSSION OF THE RESULTS

Boundary Shear Force on the Assumed Interface Planes

Using the developed boundary shear stress distribution using equation (11), the calculated ($\%S_{fp}$) are given in Table 2 (column 5). The variation between the calculated ($\%S_{fp}$) and observed values for all the compound channels comprising 62 runs for different geometry [i.e. α =2.0, 2.2, 3.0, 3.67, 4.0, 4.0, 4.2, 4.4 and 6.67] are shown in Figure 8. In the same plot the variation of calculated ($\%S_{fp}$) by previous investigators (i.e. equation 1 and equation 4) are also shown. The correlation statistics estimate indicates high correlations (R^2 = 0.98) when using the equation (11). However the results obtained using equations (1) and equation (4) provides correlation coefficients are 0.68 and 0.74 respectively. The standard error of estimate between observed and calculated values of ($\%S_{fp}$) using the proposed model for the experimental channel are found to be minimum when compared to the previous models as shown in Figure 9. All the equations are tested for their applicability with global data sets and found to be minimum for equation (11). This proves the adequacy of the developed methods. The individual error and standard error for a series of experimental runs are computed using following equations:

$$Error\ (\%) = \frac{(\%S_{fpc} - \%S_{fpm})}{\%S_{fpm}} \times 100 \qquad (12a)$$

where $\%S_{fpc}$ is the calculated ($\%S_{fp}$) and $\%S_{fpm}$ is the measured ($\%S_{fp}$). Similarly, stand error of estimation are also found using equation (12b) given as

Standard error

$$= \sqrt{\frac{\sum \left[\frac{(\%\ S_{fpc} - \%\ S_{fpm})}{\%\ S_{fpm}} \times 100 \right]^2}{N}} \qquad (12b)$$

Where, N = no of overbank flow depths observations for each channel geometry.

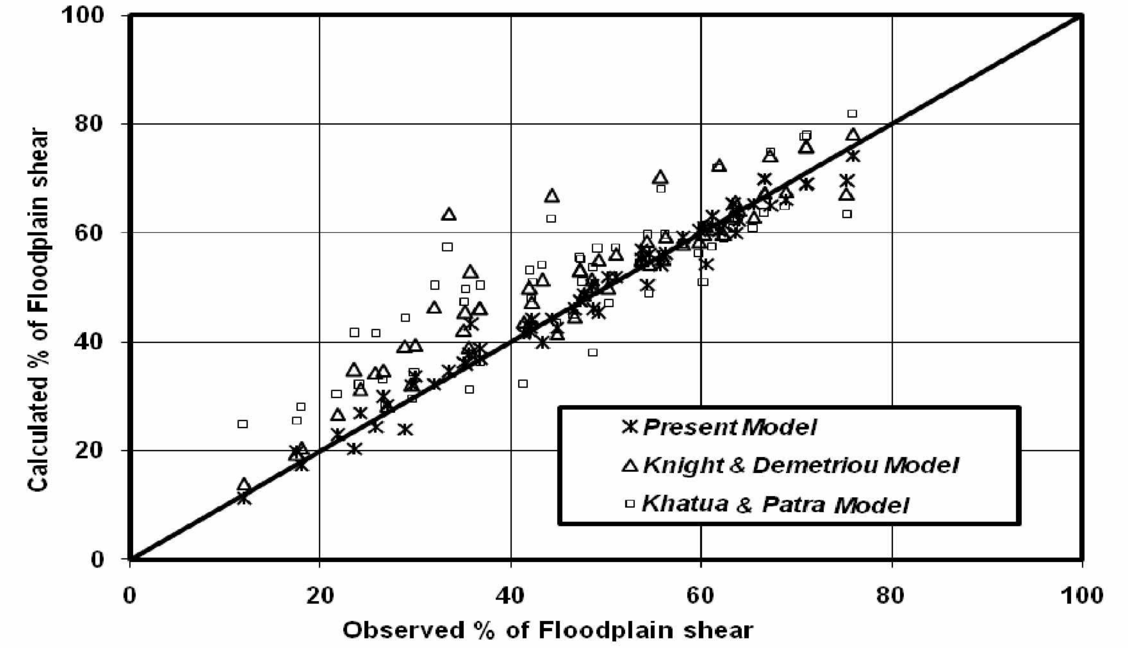

Figure 8 Variation of observed value and modeled value of ($\%S_{fp}$)

Apparent Shear Force across the Assumed Interface Planes

Selection of suitable interfaces for calculating conveyance by divided channel method (*DCM*) becomes easier once we know the apparent shear in different assumed interfaces. Toebes and Sooky [20] carried out laboratory experiments on two stage 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], Khatua [2008] 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. 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 *DCM*. This apparent shear stress is higher than the bed-shear stress at low floodplain depths and reduces gradually as β increases. For example, for the experimental channel the apparent shear stress is 13.5% per unit length of the vertical interface plane for a flow depth of 14.12cm ($\beta = 0.15$) and the apparent shear decreases as the flow depth increases and reaches 9.1 % per unit length of the vertical interface plane for a flow depth of 20.21cm ($\beta = 0.406$ in Table 1) . Similar observations are also observed in horizontal and diagonal interface plane for the channel. This follows a similar trend for channels of other investigators(e.g., Wormleaton, et al. [1980, 1982], Seckin [2004] and Mohaghegh and Kouchakzadeh [2008] etc.), Percentages of apparent shear force for the assumed vertical, horizontal, and diagonal interface planes may be calculated using (8) if $\%S_{fp}$ is evaluated using (11).

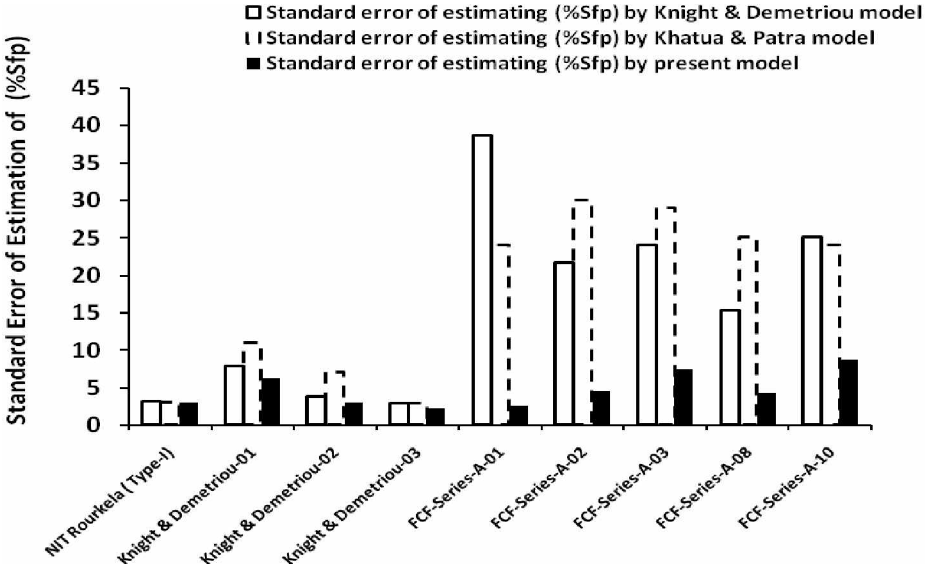

Figure 9 Standard error of estimation of ($\%S_{fp}$).

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 to the wetted perimeter does not make sufficient allowance for discharge calculation for all depths of flow over floodplain. It results either overestimate or underestimate of the discharge results because of not taking due care of the momentum transfer in terms of apparent shear at the respective interfaces. 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 or floodplain respectively to obtain the correct discharge. If apparent shear is very large for an over bank flow depth, compared to the boundary shear than the selection of respective interface plain gives erroneous discharge results for the compound channel. The apparent shear in the assumed interface of a compound channel helps in the proper selection of interfaces for discharge calculation. When the apparent shear is negligible for any chosen interface, then the interface length is not included to the wetted perimeter for the sub sections discharge calculation while using the divided channel method for discharge calculation. After finding the sub section discharges, the section discharge is obtained by adding the individual sub section discharges.

CONCLUSIONS

The following conclusions are drawn:

1. The distribution of boundary shear along the perimeter of straight compound channels is examined, relationship to predict boundary shear distribution for all types of geometry is proposed. For the compound channels the important parameters effecting the boundary shear distribution are relative depth (β) and the width ratio (α) and the relative roughness (γ). These three dimensionless parameters are used to form general equations representing the total shear force percentage carried by floodplains. The proposed equations give good result with the observed data.
2. The momentum transfer i.e. apparent shear stress across the assumed interface plains has a direct relationship with the boundary shear stress distribution of a compound channel. Furthermore the stage-discharge relationship of a compound channel using divided channel method is decided only after finding the apparent shear stress across the interface planes. The present equations for estimating the boundary shear stress distribution and hence the apparent shear is good for $\alpha > 10$ while the previous models developed by the investigators gives $\%S_{fp}$ more than 100 % when applied to a compound channel of wider floodplains.
3. The proposed boundary shear stress distribution models have been validated using data of Knight and Hamed [1984] and with the data of FCF (e.g., Myers and Brennan[1990]) giving the least error the standard error of estimation for all channels data when compared to the previously developed models.

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