SELECTION OF INTERFACE FOR DISCHARGE PREDICTION IN A COMPOUND CHANNEL FLOW

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ABSTRACT

River engineers often analyze the overbank flows using subdivision techniques through the selection of assumed interface planes. A wrong selection of interface planes between the main channel and floodplain accounts for transfer of improper momentum, which inculcates error in estimation of discharge for compound channel section. Distribution of apparent shear stress between the main channel and floodplain gives an insight into the magnitude of momentum transfer based on which the discharge estimation using divided channel methods is decided. In the present study, experimental results of momentum transfer at various interface plains for straight and meandering compound channels are presented. Momentum transfer and boundary shear distribution are found to be dependent on the dimensionless parameters viz., overbank flow depth ratio, width ratio, sinuosity, and the orientation of the interfaces. The developed equation helps to predict the discharge carried by compound channels of different geometry and sinuosity. The present study indicates that for a straight compound channel, the horizontal division method provides better discharge results for low overbank flow depth and diagonal division method is good for higher overbank flow depths. The best discharge results for a meandering compound channel are obtained through diagonal division method for low overbank flow depths and vertical division method is good for higher overbank flow depths. The adequacies of the present results are verified using present experimental data, and the data collected from the large channel facility (*FCF*) at Wallingford, UK. These methods agree well when applied to some natural river data.

Keywords: apparent shear, compound channel, discharge estimation, floodplain, interface planes, main channel, meandering river.

1 INTRODUCTION

Reliable estimation of discharge is essential for the design, operation, and maintenance of open channels. During high stages in the rivers, it is quite common that the river discharge overtops its bank and spreads to its adjoining floodplains that carry a part of the flow. At this high stage, the cross-sectional geometry of flow undergoes a steep change. The channel section becomes compound. The difference of hydraulic conditions in the main channel and floodplain in a compound river generates large shear layers due to the difference of mean subarea velocity between the main channel and the adjoining floodplain flow. Just above the bankfull stage, the velocity of main channel flow is much higher than the floodplain velocity. Therefore, the flow in the main channel exerts a pulling or accelerating force on the floodplain flow, which naturally generates a dragging or retarding force on the flow through the main channel. This leads to the transfer of momentum between the main channel and floodplain (Fig. 1). The interaction effect is very strong at just above bankfull stage and decreases with increase in the depth of flow over floodplain. The flow process reverses at still higher depths of flow in the floodplain. The relative ‘pull’ and ‘drag’ of flow between faster and slower moving sections of a compound section complicates the momentum transfer between them. Failure to understand this process leads to either overestimation or underestimation of the discharge leading to the faulty design of a compound channel.

Discharge estimation methods currently employed in river modeling are based on historic empirical formulae. The traditional discharge predictive methods for compound channels either use the Single Channel Method (SCM) or the Divided Channel Method (DCM). In the laboratory, the mechanism of momentum transfer between the deep main channel section and shallow floodplain was

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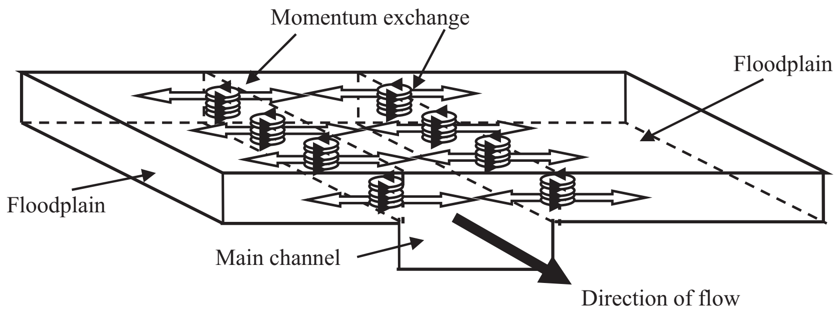

Figure 1: Schematic view of momentum transfer in a compound channel.

first investigated and demonstrated by Zheleznvakov [1] and Sellin [2]. Imaginary interface planes running from the junction between the main channel and floodplain are used to separate the main channel from the floodplain of the compound section. Wright and Carstens [3] observed that the estimation of discharge using the DCM for compound sections compared well with the observed values, although segment discharges varied up to +10%. They included the interface length to the wetted perimeter of the main channel only, as they considered that the slower flowing floodplain flow exerted a drag on the faster flowing main channel flow. Yen and Overton [4] used isovel plots to locate interface planes of zero shear.

The DCM divides a compound section into hydraulically homogeneous subsections generally by vertical, inclined, or horizontal division lines that lead to an averaged flow velocity for each subsection (e.g. Chow [5]). Therefore, this method predicts better overall discharge as compared to SCM (Weber and Menéndez [6] and Patra and Khatua [7]) but it overestimates the flow in main channel and underestimates the flow in the floodplain due to the neglect of lateral momentum transfer. While using the vertical interface division of DCM, Wormleaton et al. [8] proposed an apparent shear stress ratio, as the useful yardstick in selecting the best interface planes. Toebes and Sooky [9] carried out laboratory experiments on two composite channel sections and showed that a nearly horizontal fluid boundary located at the junction between the main channel and floodplain would be more realistic than a vertical fluid boundary along the banks of the meandering channel in dividing the compound channel for discharge calculation. Using the data of the Flood Channel Facility at HR Wallingford, UK, Greenhill and Sellin [10] reported a method to estimate the discharge for meandering compound channels using Manning's equation and by extending the conventional DCM. Holden [11], Prinos and Townsend [12], Lambert and Myers [13], and Patra and Kar [14] also proposed zero shear interface plains to nullify the lateral momentum transfer. The empirical shear stress formulae to calculate the apparent shear at the shear layer between main channel and floodplain (Knight and Hamid [15]) are limited to a particular geometry and are difficult to apply to other data (Knight and Shiono[16]). Ackers [17] proposed an empirical correction to the DCM known as Coherence Method (COHM) that is recommended by the UK Environmental agency, Bristol, UK. This empirical approach requires assumptions on some geometrical parameters when used with asymmetrical channels. Shiono and Knight [3] developed a two-dimensional (SKM) method based on the analytical solution to the depth averaged form of the Navier–Stokes equation. Lambert and Myers [13] developed the weighted DCM (WDCM) to compute the stage discharge capacity for a compound channel based on estimation of the subsection mean velocities. Mohaghegh and Kouchakzadeh [18] carried out laboratory test and found that COHM gave less satisfactory results when compared to DCM and SCM. Toebes and Sooky [9] carried out laboratory experiments and showed that the horizontal interface method would be more realistic than other interface methods. In the calculation, they included the horizontal interface to the wetted perimeter of the main channel to get the most accurate overall discharge results. The interaction phenomenon and the discharge assessment for compound sections using DCM were presented by many other researchers as well (e.g. Myers and Elsawy [19], Bousmar and Zech [20], Knight and Demetriou [21], Wright and Carstens [3], Seckin [22], Bhowmik and Demissie [23], Patra *et al.* [24] Kejun Yang *et al.* [25], Khatua [26], Abril and Knight [27], Huthoff [28], etc.). Failure of most subdivision methods were due to the improper accounting of the complicated interaction between the main channel and floodplain flows, more particularly for channels having wide floodplains.

Investigators have proposed different interface planes to calculate the total discharge carried by a compound channel section. These assumptions either include or exclude the interface length to the wetted perimeter, which does not make sufficient measures for discharge calculation for all depths of flow over floodplain. It results in overestimation or underestimation of the discharge calculation. The present study is aimed at understanding the general nature of the interaction between the main channel and the floodplain flows in compound sections. The work presented in this paper is based on a series of compound channel sections with width ratio varying from 2 to 6.64, flow depth ratio varying between floodplain to main channel flow up to 0.404, and sinuosity varying from 1.0 to 1.44. In one series of experiment, all the surfaces of main channel and floodplains are roughened uniformly. An attempt has been made to develop a stage–discharge relationship of compound channels based on the study of boundary shear distribution in such channels having different geometry and sinuosity, which quantifies the momentum transfer between subsections in a compound channel.

2 THEORITICAL CONSIDERATIONS

2.1 Shear force on the assumed interface planes

Study of apparent shear stress distribution at different interfaces of a compound channel originating from the main channel and floodplain junction is helpful for *DCM* to choose appropriate subdivision lines for separating a compound channel into subsections for discharge assessment. Figure 2 shows the different interfaces of a compound channel originating from the junction point. Any assumed interfaces *o-p* lying between extreme interfaces *oa* and *oe* describes an angle θ with the vertical line at *o*. The most commonly vertical, horizontal, and diagonal plains of separation are represented by the interface lengths *o-g*, *o-c*, and *o-o* respectively. Various boundary elements comprising the wetted parameters are labeled as (1), (2), (3), and (4), where (1) denotes the vertical wall(s) of floodplain of length $[2(H - h)]$, where H = total depth of flow from main channel bed, h = depth of main channel, (2) denotes floodplain beds of length $(B - b)$, where B = total width of compound channel, and

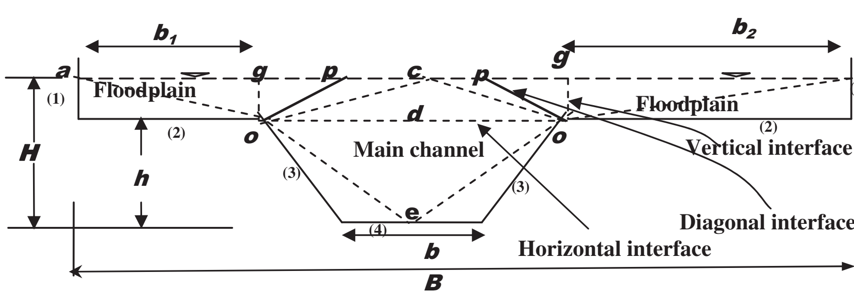

Figure 2: Interface planes dividing a compound section into subsections.

b = width or bed of main channel represented by (4), and (3) denotes two main channel walls of length ($2h$). Experimental shear stress distribution at each point of the wetted perimeter is numerically integrated over the respective sublengths 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 (1) through (4). Percentage of shear force carried by floodplains comprising elements (1) and (2) is represented as $\%S_{fp}$ and that for main channel comprising elements (3) and (4) is represented as $\%S_{mc}$.

Following the work of Knight and Demetriou [21], Knight and Hamed [15] proposed an equation for $\%S_{fp}$ for a compound channel section as

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

Equation (1) is applicable for the channels having equal surface roughness in the floodplain and main channel. For non-homogeneous roughness channels, eqn (1) is improved as

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

where, α = width ratio = B/b , β = relative depth = $(H - h)/H$, γ = the ratio of Manning's roughness n of the floodplain to that of the main channel. The exponent m can be evaluated from the relation

$$m = 1/\left\lfloor 0.75\, e^{0.38\alpha}\right\rfloor. \tag{3}$$

For homogeneous roughness section ($\gamma = 1$), eqn (2) reduces to the form of Knight and Hamed, [15] that is, eqn (1). Due to complexity of the empirical equations proposed by the previous investigators, a regression analysis was made by Khatua and Patra [29] and they proposed an equation for $\%S_{fp}$ as

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

For meandering channel with floodplain, the distribution of shear stress is more nonuniform than straight channel and hence is modified to incorporate the meandering effect. It has been observed from the experimental results that the percentage of boundary shear is inversely proportional to sinuosity (S_r) and exponentially vary with amplitude(ε)/floodplain width (B) ratio, that is, R. Finally a general equation for meandering compound channel is proposed as

$$\%S_{fp} = 1.451\,\beta^{0.1833}\;(38.269\ln\alpha + 3.6262)\;\;[\frac{(1 + \alpha\,\mathrm{Re}^{-13.25\,\beta\delta})}{S_r}]\{1 + 1.02\sqrt{\beta}\log\gamma\}, \tag{4b}$$

where δ = aspect ratio of the main channel = b/h; the details and derivation of eqn (1) is described by Knight and Hamed [15]. The adequacy of eqn (4) is described in Khatua and Patra [29].

Equation (2) by Knight and Hamed [15] is good for the straight compound channels having width ratio α up to 4. Similarly, Khatua and Patra [29] have shown the adequacy of α up to 5.25 for both straight and meandering channels. Khatua [26] further presented a general equation which is valid for a compound channel of all types of geometry as

$$\%S_{fp} = 4.105\left[\frac{100\,\beta(\alpha - 1)}{1 + \beta(\alpha - 1)}\right]^{0.6917}\{1 + 1.02\sqrt{\beta}\log\gamma\}. \tag{5}$$

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, which is given as

$$\rho g A_{mc} S = \int_{mc} \tau dp + ASF_{ip} \quad \text{or} \quad ASF_{ip} = \rho g A_{mc} S - \int_{mc} \tau dp, \tag{6}$$

where 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. Prinos and Townsend [12] proposed an empirical equation for the apparent shear stress (τ) in N/m^2 given as

$$\tau = 0.874\ (\Delta V)^{0.92}\ (\beta)^{-1.129}\ (\alpha)^{-0.514}, \tag{7}$$

where ΔV is the difference of section mean velocity between the main channel and floodplain in meter per second. Equation (7) is purely empirical. The unit associated with the numerical value 0.874 of eqn (7) is N-sec$^{0.92}$/m$^{2.92}$. This equation, proposed for straight compound channels, was found to apply to the results of Wormleaton [30] and Knight and Demetriou [21] only. For both the meandering and straight compound channels, further analyses are made here to derive a simple expression for the apparent shear at any interface plane.

Consider an arbitrary interface *op*, lying between extreme interfaces *oa* and *oe* which makes an angle θ to vertical line at the junctions (Fig. 2). Two situations of locating interface plains can arise. When the interface *op* lies between *oa* and *oc*, the ranges of angle θ can be defined as $\tan\theta \le \frac{b}{2(H-h)}$ and $\tan(-\theta) \le \frac{b_1}{(H-h)}$ or $\frac{b_2}{(H-h)}$, where b_1 and b_2 are the lengths of floodplain bed at both sides measured from vertical interface. For a symmetrical compound channel $b_1 = b_2 = (B-b)/2$, simplifying, the expression for percentages of apparent shear force in the assumed interface is given as

$$\%ASF_{ip} = 100\frac{(\delta - \beta^2 \tan\theta)}{\delta\{1+(\alpha-1)\beta\}} - (100 - \%S_{fp}). \tag{8a}$$

The second case is when interface *op* lies between *oc* and *oe*. The ranges of angle θ for this situation can be calculated from the relations given as $\tan\theta \le \frac{2h}{b}$ and $\tan\theta \ge \frac{b}{2(H-h)}$. Simplifying we get

$$\%ASF_{ip} = 100\left\{\frac{\delta\cot\theta - 4\beta + 4}{4\{1+(\alpha-1)\beta\}}\right\} - (100 - \%S_{fp}). \tag{8b}$$

It is seen that the magnitude of momentum transfer at an interface using eqn (8a) or (8b) depends on the dimensionless parameters like α, β, and $\%S_{fp}$. For any compound river section both the parameters α and β are known. The third parameter $\%S_{fp}$ can be calculated using eqns (4) or (5).

3 EXPERIMENTAL DETAILS

In the present work, in view of investigation of momentum transfer phenomenon across interfaces of both straight and meandering compound channel, experimental data of a straight and a meandering compound channel (say Type 1 and Type II) along with three types of meandering compound channels from IIT Kharagpur (say Type III, Type IV, and Type V) are presented in this paper. Experiments in Type I and Type II have been conducted at the Fluid Mechanics and Hydraulics Laboratory

Table 1: Details of geometrical parameters of the experimental compound channels.

Test channel	Longitudinal slope (S)	Main channel width (b) mm	Main channel depth (h) mm	Main channel side slope (s)	Width ratio (α)	Sinuosity	Observed discharge (Q) range in cm^3/s	Range of relative depth (β)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Type I	0.0019	120	120	0.0	3.67	1.00	8726–39071	0.118–0.461
Type II	0.0031	100	100	0.0	4.81	1.44	9006–31358	0.12–0.34
Type III	0.004	100	100	0.0	2.13	1.21	5800–11200	0.17–0.34
Type IV	0.004	100	100	0.0	4.18	1.21	5800–8450	0.17–0.29
Type V	0.00278	440	250	0.0	3.14	1.04	94535–108583	0.15–0.21
Knight and	0.00096	304	76	0.0	2.00	1.00	5200–17100	0.108–0.409
Demetriou [21]	0.00096	456	76	0.0	3.00	1.00	5000–23400	0.131–0.491
	0.00096	608	76	0.0	4.00	1.00	4900–29400	0.106–0.506
FCF Series-A	1.027×10^{-3}	1500	150	1.0	6.67	1.00	208200–1014500	0.056–0.400
channels	1.027×10^{-3}	1500	150	1.0	4.20	1.00	212300–1114200	0.0414–0.479
	1.027×10^{-3}	1500	150	1.0	2.20	1.00	225100–834900	0.0506–0.500
	1.027×10^{-3}	1500	150	0.0	4.00	1.00	185800–1103400	0.0504–0.499
	1.027×10^{-3}	1500	150	2.0	4.40	1.00	236800–1093900	0.0508–0.464

of the Department Civil Engineering, National Institute of Technology, Rourkela, India. Type I is a symmetrical straight compound channel having uniform roughness both in main channel and floodplain. Type II a meandering compound channel is also symmetrical and has uniform roughness in both main channel and floodplain. Type III and Type IV are asymmetrical with only floodplain attached to one side of the main channel. Type V channel is symmetrical with two equal floodplains attached to both sides of the main channel. The centerline of the entire meandering channel is taken as sinusoidal. The summary of experiments conducted is given in Table 1.

Details of the experimental setup and procedure concerning the flow and velocity observations in meandering channels with floodplains of Type I and Type II are given in Khatua [26] or in http://ethesis.nitrkl.ac.in/81/1/thesis-final-khattuva.pdf. Similarly for Types III, IV and V channels, the details are reported earlier (Patra and Kar [14]; and Patra and Kar [24]). Plan forms of the meandering experimental channels with floodplains for both symmetrical and asymmetrical compound channels are shown in Fig. 3 and photograph of Type II symmetrical compound channel is shown in Fig. 4. Details of experimental setup (Type II meandering experimental channels with floodplains) are also shown in Fig. 5.

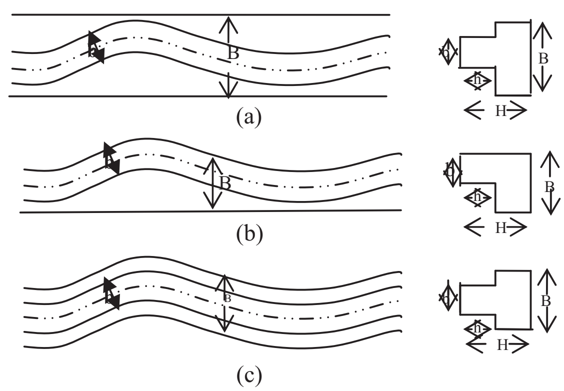

Figure 3: Plan forms of meandering channels with floodplains.

Figure 4: Type II meandering channels with floodplains.

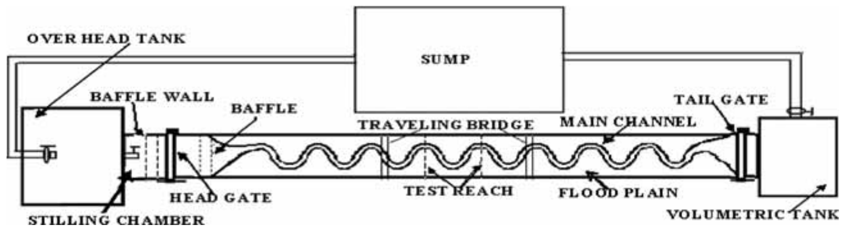

Figure 5: Plan of Type II experimental setup showing meandering channels with floodplains.

4 RESULTS AND DISCUSSIONS

4.1 Apparent shear stress results

For any given interfaces that lie between extreme interfaces *oa* and *oe*, the angle θ is known. Equation (8) can be directly used to find the apparent shear along any interfaces easily. This equation also helps to plot the variation of apparent shear along interfaces and flow depths so as to find a suitable location of interface for accurate discharge prediction.

Review of previous studies show that they do not provide sufficient information on the momentum transfer across the assumed interfaces. In actual situation, the minimum apparent shear force may occur at an interface making an angle θ for various widths and depth ratios (β) in a compound channel. Keeping this in view, a series of experimental runs are conducted in both straight and meandering compound channels at NIT Rourkela by varying the depth ratios. The momentum transfer across different interfaces for each overbank depths are analyzed by using the derived eqn (8). The apparent shear at the interfaces for each overbank depths are plotted between the region *oa* and *oe* of the compound channel at 5° intervals. The results for straight and meandering compound channels are shown in Figs. 6 and 7, respectively. The convention for momentum transfer is positive from the main channel to floodplain and that from floodplain to main channel, it is taken as negative. When we separate main channel from floodplain for straight and meandering compound channels, it is seen that the maximum positive apparent shear occurs along the extreme interface *oa* and the apparent shear gradually decreases as the interface moves to the channel center. After reaching the interface plane of zero shear, the apparent shear at the planes becomes negative with maximum negative occurring at the other extreme interface *oe*. This concludes that for any overbank depth, maximum positive momentum transfer takes place from main channel to floodplain, if we consider the interface *oa*, and the highest maximum negative momentum takes place from floodplain to main channel, if we consider the interface *oe*.

For straight compound channel (Type I) with lower overbank, the interface plain of zero shear is found near the horizontal interfaces (approximately at $\theta = 99°$ for the lowest over bank depth), and for higher overbank depths, the interface plane of zero apparent shear is observed near a diagonal line of separation (approximately at $\theta = 40°$ for the highest overbank). Similarly, for Type II meandering channel, the interface plane of zero shear lies at around ($\theta = 109°$) that is with respect to horizontal line ($\theta = 19°$) and is located toward lower main channel. For the highest overbank depth, the interface of zero shear lies close to the vertical interface. The apparent shear in the vertical interfaces is found to be 13.5% of the total shear for the overbank flow depth of 2.12 cm ($\beta = 0.15$). It is found that the apparent shear decreases as the flow depth increases and reaches to 9.1% for a overbank flow depth of 8.21 cm ($\beta = 0.406$).

Again for the meandering channel (Type II) at low overbank depths, the horizontal interface shows zero momentum transfer. For higher overbank depths, the interface plane of zero shear should lie little (20°) above the horizontal interfaces. Of course, inclusion of interface lengths like V_{ie} for

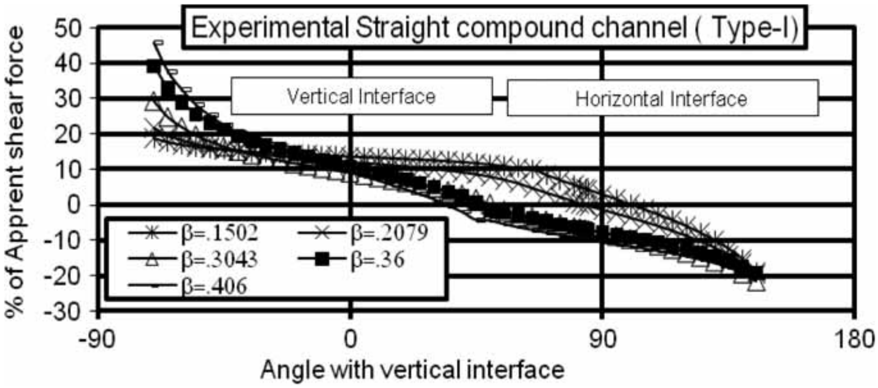

Figure 6: Apparent shear along various interface planes of a straight compound channel.

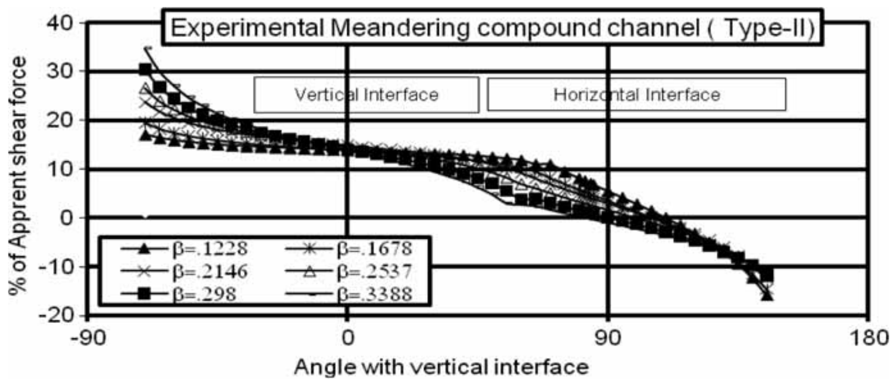

Figure 7: Apparent shear along various interface planes of a meandering compound channel.

higher overbank depth will compensate the apparent shear giving better discharge results for meandering compound channels. For straight and meandering compound channels, the apparent shear along the vertical, diagonal, or horizontal interfaces is never zero or equal to the average shear of the main channel/floodplain wetted perimeter. The apparent shear is found to vary with overbank depths and its location. For overbank flows, we use conventionally the simple inclusion or exclusion of interface length to the wetted perimeter for discharge evaluation for each subsection (through Manning's equation following DCM). The approaches either overestimate or underestimate the compound channel discharge that have been demonstrated by several authors (Wormleaton *et al*. [8], Knight and Demetriou [21], Knight and Hamed [15], Greenhill and Sellin [10], Patra and Kar [14], Ozbek *et al*. [31]). Use of the conventional interface method with the proper addition of interface length to the wetted perimeter of main channel subsection and subtraction of the proportionate length of interface from the floodplain wetted perimeter is expected to give better discharge results using DCM. For the present test channels (Types I and II) and the test channels of other investigators (Knight and Demetriou (1983) and FCF-Series A channels etc.), it is demonstrated that proposed modification to the conventional methods give better results for both straight and meandering compound sections. Hence, plotting the momentum transfer using the developed eqn (8a) and (8b) can be useful in selecting an interface plain for straight and meandering compound channels into subsections for discharge calculations using DCM.

4.2 Estimating discharge using different approaches

If Q_c represents the calculated discharge and Q_m the measured discharge, the percentages of error for each series of experimental runs are computed using the following equation:

$$Error(\%) = \frac{(Q_c - Q_m)}{Q_m} \times 100. \tag{9}$$

As already stated, proper selection of the interface plane is required using the value of the apparent shear at the assumed interface plane. In *DCM*, investigators either include or exclude the interface lengths in calculating the wetted perimeter for the estimation of discharge. By including a length ['*H-h*' for vertical (*VDM*-II), of '*b*' for horizontal (*HDM*-II), and $\sqrt{(H-h)^2 + b^2}$ for diagonal interface (*DDM*)] to the wetted perimeter of the main channel, a shear drag of magnitude equal to the interface length times the average boundary shear is included. However, in such situations, the actual interface shear is not considered. Similarly, by excluding these lengths, a zero shear along these interfaces is assumed. The results for such cases are termed as *VDM-I*, *HDM-I*, and *DDM-I* respectively, shown in Figs. 8 and 9.

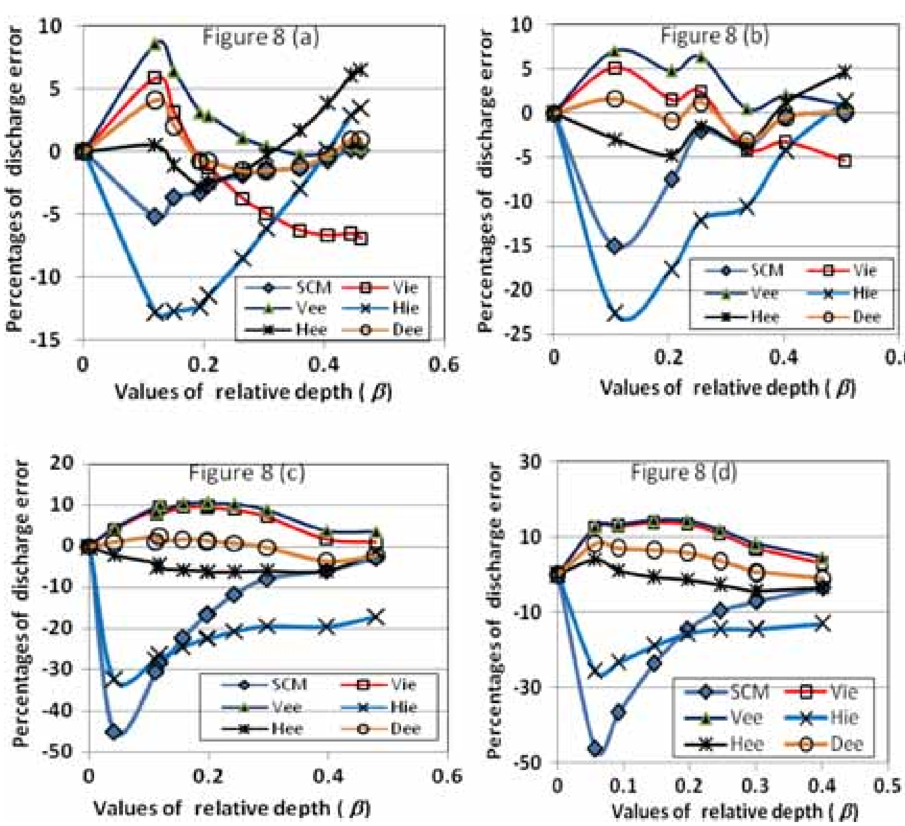

Figure 8: a–d (clockwise from top left): Variation of percentage error of discharge with relative depth (Type I of α = 3.67), Knight and Demetriou[21] of α = 4, FCF-Series A-α = 4.2, and FCF-Series A-α = 6.67) by various approaches for various straight compound channels data *[SCM, V_{ee} – (VDM-I), V_{ie} – (VDM-II), H_{ee} – (HDM-I), H_{ie} – (HDM-II), D_{ee} – DDM].*

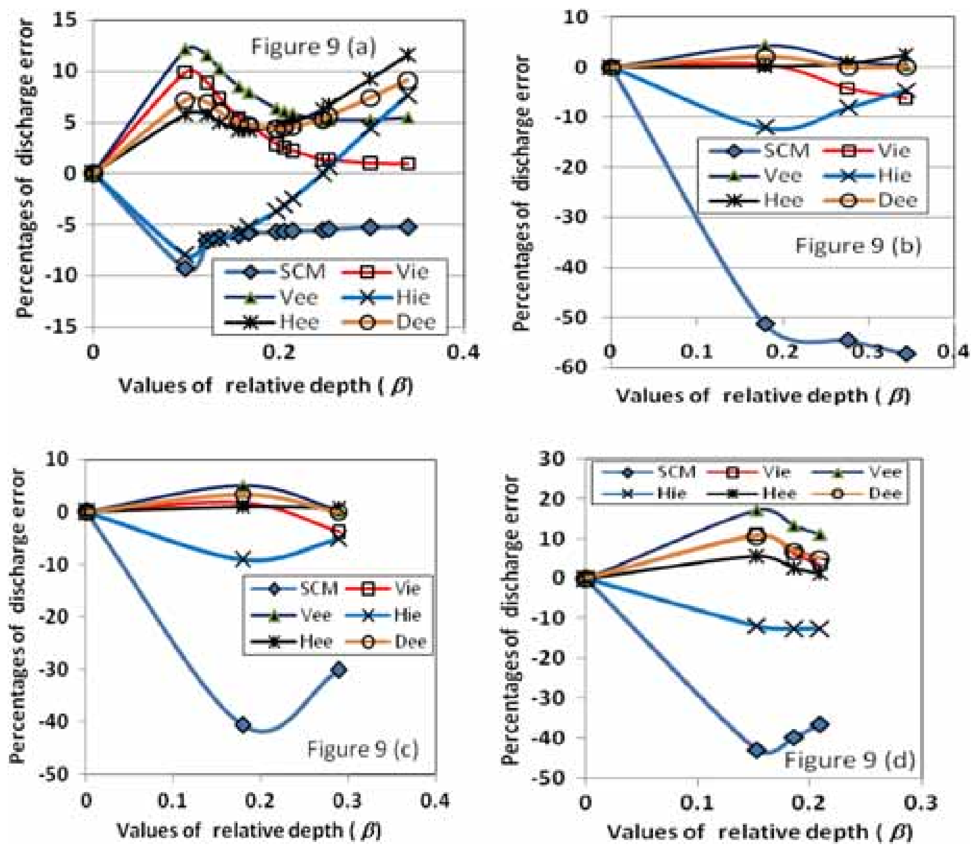

Figure 9: a–d (clockwise from top left): Variation of percentage error of discharge with relative depth by various approaches for various meandering compound channels data [Type II (S_r = 1.44), Type III (S_r = 1.21), Type V (S_r = 1.04), and FCF-Series B –(S_r = 1.34) *[SCM, V_{ee} – (VDM-I), V_{ie} – (VDM-II), H_{ee} – (HDM-I), H_{ie} – (HDM-II), D_{ee} – DDM].*

4.3 Validations of the methods for straight channel

Using the above discussed approaches, the discharge error estimation for the straight compound channel of Type I, one set of channels of Knight and Demetriou [21] and a channels from the *FCF*-Series *A* are plotted in Fig. 8a–d, respectively.

4.4 Validation of the methods for meandering compound channels

Using the above discussed common approaches, the discharge error estimation for the experimental meandering compound channel Type II and for sets of asymmetrical, rough channels of Patra and Kar [14] and for a channel from the *FCF*-Series *B* are plotted in Fig. 9a–d, respectively.

Application of these methods to the set of compound channels showed that *SCM* gives higher discharge error at low overbank flow depths [e.g. in Fig. 8d, maximum discharge error for α = 6.67 is more than 45%]. For all the compound channels studied, the error from *HDM*-I (curve H_{ee}) is less than that from *HDM*-II (i.e. curve H_{ie}), which is in line with the findings of Seckin [22]. Similarly, *VDM*-II (curve V_{ie}) gives better discharge results than *VDM*-I (curve V_{ee}), which is in line with the findings of Mohaghegh and Kouchakzadeh [18]. *VDM*-1 (curve V_{ee}) provides higher error for compound channels of wider floodplain (e.g. for $\alpha = 6.67$ in Fig. 9). Based on the present analysis, it can be concluded that *HDM*-I is better at low overbank depths for both straight and meandering compound channel and *DDM* is better for higher overbank depths in case of straight channel, and VDM-II is better for higher overbank depths for all meandering compound channels. In the present case, it is found that VDM-I also gives better discharge results for small width ratio compound channels at low relative flow depths.

5 PRACTICAL APPLICATION OF THE METHODS

Discharge prediction approaches are also applied to some natural straight river data, that is, river Main (e.g. Myers and Lynness [32]; Mc Gahey *et al*. [33]) and meandering river data of river Baitarini (e.g. Patra and Kar [14)]. The rivers are having uniform roughness and compound in cross sections (Figs. 10, 11, and 12). The river Baitarani has a sinuosity of 1.334 at the gauging site. At the site, the values of b, h, and δ and the amplitude of the meander are scaled as 210, 5.4, 38.9, and 425 m, respectively. Discharge results based on different methods applied to these rivers are shown in Fig. 13(a) and (b). In the natural straight compound river section also, *HDM-I* gives good discharge results at low overbank depth and *DDM* shows good results at higher overbank depths as compared to other approaches. Similarly for a natural meandering compound river section also, *HDM-I* is showing good discharge results at low overbank depth and *VDM-II* at higher depths. However, for the present natural channels having low width ratios (i.e. $\alpha < 3.00$), *VDM-I* is also found to give

Figure 10: Morphological cross section of overbank flow in River Main.

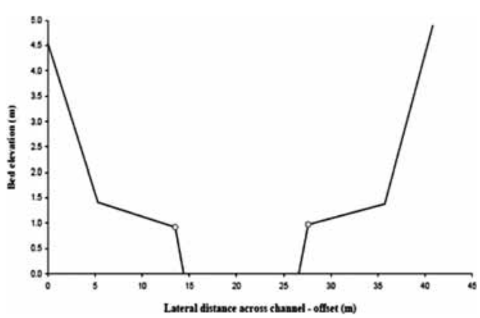

Figure 11: River Main cross section (Myers and Lynness [24]).

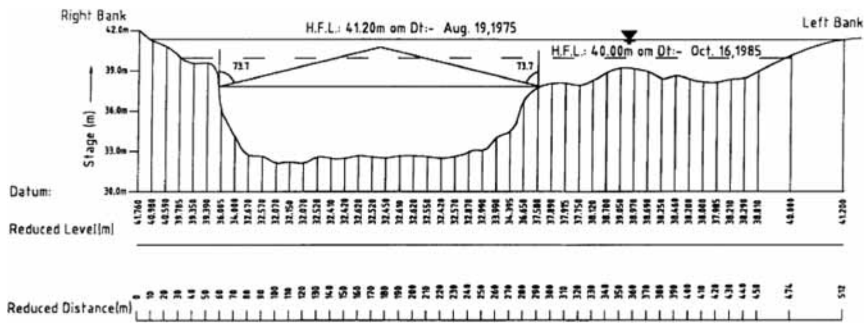

Figure 12: Cross section of meandering river Baitarini at Anandpur site Orissa, India (Patra and Kar [14]).

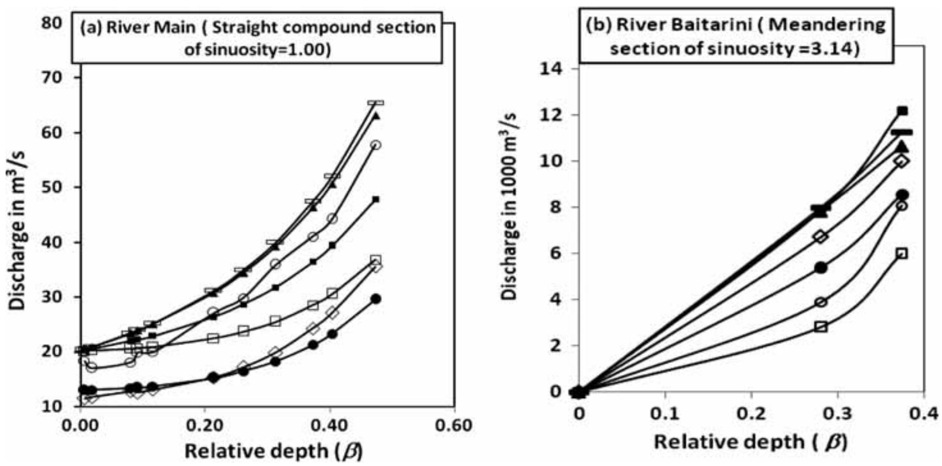

Figure 13: Variation of calculated and observed discharge with relative depth using different approaches for (a) River Main and (b) River Baitarini [Notations : —o— Actual, —◇— *SCM*, —□— *HDM-1*, —•— *HDM-1I*, —▬— *VDM-1*, —▲— *VDM-1I*, —■— *DDM*].

better discharge results (Table 2). This may possibly be due to low intensity of interaction between floodplain and main channel flow. This gives a good indication of the efficacy of the developed momentum transfer and boundary shear distribution model for compound channel sections. Thus, the present work helps in the proper selection of an interface plain in a compound river channel for predicting better stage–discharge relationships.

6 SUGGESTED COMPUTATIONAL PROCEDURES FOR PRACTICAL USE

The following steps may be followed by the practitioner and designers of river engineering in the field.

1. For any compound river section of given geometry, both the dimensionless parameters α and β may be calculated using $\alpha = B/b$ and $\beta = H–h/H$. (All notations as explained earlier.)
2. Knowing the values of α, β, and γ (the ratio of Manning's roughness n of the floodplain to that of the main channel), $\%S_{fp}$ may be calculated using eqn (5).

Table 2: Geometrical properties, surface conditions, and discharge error by different approaches for river Baitarini and river Main.

River Baitarini								River Main							
Av. bank full depth = 5.40 m; Top width of main channel = 230 m; Bed slope of main channel = 0.0011; Surface condition of main channel = sandy surface; Bed slope of left and right floodplains = 0.0011; Surface condition of floodplain = grass vegetation; Surface condition of side bank = Erodible soil								Av. bank full depth = 0.95 m; Top width of main channel = 14.0 m; Surface condition of main channel = coarse gravel; Bed slope = 0.0029; Surface condition of floodplain = heavy weed growth and sand; Surface condition of side bank = Rip-rap							
Discharge error estimation by different approaches								Discharge error estimation by different approaches							
A	β	SCM	HDM-I	HDM-II	VDM-I	VDM-II	DDM	α	β	SCM	HDM-I	HDM-II	VDM-I	VDM-II	DDM
2.2	0.28	−14.4	−64.0	−31.4	1.6	−0.2	−50.5	1.2	0.01	−45.9	−4.6	−38.8	−3.6	−3.6	−4.1
2.4	0.37	−18.0	−50.8	−29.8	−7.9	−12.0	−33.9	1.2	0.02	−47.8	−9.2	−42.1	−6.9	−7.0	−8.4
								1.3	0.08	−43.9	−9.7	−41.4	2.8	2.4	−3.8
								1.4	0.09	−49.1	−16.3	−45.6	−2.9	−3.3	−10.0
								1.4	0.11	−47.1	−15.7	−44.9	1.4	0.8	−7.8
								1.8	0.21	−54.5	−33.3	−54.8	−7.5	−8.6	−21.7
								2.0	0.26	−53.6	−36.1	−55.7	−5.7	−7.1	−22.7
								2.3	0.31	−55.5	−42.9	−59.1	−10.4	−12.0	−28.9
								2.4	0.37	−52.5	−44.2	−58.3	−7.1	−9.3	−28.7
								2.5	0.40	−50.7	−44.5	−57.7	−5.3	−7.9	−28.5
								2.6	0.47	−50.5	−48.8	−58.9	−9.0	−12.2	−33.5

3. Next $\%ASF_{ip}$ can be calculated from eqn (8).
4. A plot for variation of $\%ASF_{ip}$ for different interface plains (in terms of angle θ with vertical interface) for different flow depths are to be done (e.g. Fig. 6 for straight and Fig. 7 for meandering channel).
5. From the plot, the interface plane of zero shear for any flow depth is selected (where $\%ASF_{ip} = 0$). The compound channel for the chosen depth is divided into subsections; the discharge for each subsection is calculated using Manning's equation and summed up to give total discharge carried by the compound channel. Since at the interface plain of zero shear, there is no transfer of momentum, so interface length is excluded in calculating the wetted perimeter of each subsection.

7 CONCLUSIONS

(I) The developed expression for boundary shear stress distribution and apparent shear stress across the assumed interface for straight and meandering compound channels is helpful in quantifying the interaction between the main channel and floodplain. These properties are found to be dependent on the overbank flow depth, width ratio, main channel aspect ratio, sinuosity, roughness, and the inclinations of interface. A particular *DCM* approach for evaluation of stage–discharge relationship in a compound channel can only be decided after examining the apparent shear stress across the different interface planes.

(II) For straight compound channels, the maximum positive momentum transfer takes place from main channel to floodplain if we consider the interface lying in the floodplain region and the highest maximum negative momentum transfer takes place from floodplain to main channel if we consider the interface lying in the lower main channel region.

(III) At low overbank flow depths, the zero apparent shear is found near the assumed horizontal interfaces for both straight and meandering compound sections. For higher overbank depths, the interface plane of zero apparent shear is observed near diagonal line for straight channel, whereas for a meandering channels, the interface plane of zero apparent shear is observed little below the horizontal interface line.

(IV) It is found that the apparent shear along the most commonly used interfaces is never zero or equal to the average shear of the subsection wetted perimeter. The apparent shear has been found to vary with overbank depths and from interface to interface.

(V) *SCM* is found to give higher discharge error at low overbank flow depths and the error reduces at high overbank flow depths. Based on the present analysis, it can be concluded that *HDM-I* is better for low overbank depths for both straight and meandering compound channel and *DDM* is better at higher overbank depths in case of straight channels. *VDM-II* is better at higher overbank depths for meandering compound channels. The adequacies of the developed equation are verified using the data from present straight and meandering channels, straight channels of Knight and Demetriou [21], and meandering compound channels of Patra and Kar [14]. Although many researchers have found the performance of *VDM-I* to be quite satisfactory, it is also found to give better discharge results for the present compound channel geometry, especially for small width ratios and low relative flow depths.

(VI) The methods are also applied to straight compound natural river sections of river Main and meandering compound river sections of river Baitarani. The present analysis gives satisfactory results to these natural river data showing adequacies of present investigations.

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