APPARENT SHEAR STRESS AND BOUNDARY SHEAR DISTRIBUTION IN A COMPOUND CHANNEL FLOW

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Abstract
The flow structure in any compound channel is a complicated process due to the transfer of momentum between the deep main channel section and the adjoining shallow floodplains. However, the boundary shear stress distribution in the main channel and floodplain greatly affects the momentum transfer. In the present work, commonly used equations of shear stress distributions across assumed interface plane originating from the junction between main channel and flood plain using Divided Channel Method (DCM) are analyzed and tested for different compound channels and their flow conditions using global data. Furthermore, a modified general expression to predict the boundary shear distribution in compound channels for different width ratios is derived that is found to provide significant improvements in the results. The modified boundary shear stress distribution approach is tested for its validity using commonly used data published in the literature and compared with existing models. Analyses are also done to suitably choose an appropriate interface plane for evaluation of stage-discharge relationship for compound channels having uniform roughness. The effectiveness of commonly used stage-discharge methods using the apparent shear stress model and boundary shear distribution models are discussed.

Keywords: MACROBUTTON MACROBUTTON Apparent Shear, Main channel, Floodplain, Compound channel, Discharge Estimation, Interface planes.

1 Introduction

During floods, a part of the river discharge is carried by the main channel and the rest is carried by the floodplains. Momentum transfer between the flow of main channel and floodplain occurs making the discharge prediction in compound channel more difficult. In the laboratory the mechanism of momentum transfer between the deep river section and shallow floodplain was first investigated and demonstrated by Zheleznvakov[31] and Sellin [24]. While calculating discharge in compound channels, a method based on ‘divided sections’ is usually employed. 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 [29] observed that the calculation of discharge using the ‘‘divided channel method’’ for compound sections compared well with the observed values although segment discharges varied up to +10%. They included the interface length in the wetted perimeter of the main channel subdivision only, as they considered that the slower flowing floodplain flow exerted a drag on the faster flowing main channel flow. Yen and Overton [30] used isovel plots to locate interface planes of zero shear.

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 [4]). These approaches have the advantage of recognizing a particular hydraulic property in the respective compartments. Therefore, this method predicts better overall discharge as compared to SCM (Weber and Menéndez [27], and Patra and Khatua [20]) 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. [28] proposed an apparent shear stress ratio, as the useful yardstick in selecting the best interface planes. Holden [6], Lambert and Myers [14],and Patra and Kar [10] also proposed zero shear interface plains that nullify the lateral momentum transfer. The empirical shear stress formulas to calculate the apparent shear at the shear layer between main channel and floodplain (Knight and Hamid [12]) are limited to a particular geometry and are difficult to apply to other data (Knight and Shiono[13]). Based on the published data, Ackers [1] proposed an empirical based correction to the DCM know as Coherence Method (COHM) that is recommended by the UK Environmental Agency Bristol. This empirical approach requires assumptions on some geometrical parameters used for example with asymmetrical channels. Shiono & Knight [25] developed a 2-dimensional (SKM) method based on the analytical solution to the depth averaged form of the Navier-Stokes equation. Lambert and Myer [14] developed the weighted divided channel method (WDCM) estimating the stage discharge capacity for a compound channel based on estimating the sub-section mean velocities.

Mohaghegh and Kouchakzadeh [18] carried out laboratory test and found that COHM gives less satisfactory results when compared to the DCM and SCM. Toebes and Sooky [33] carried out laboratory experiments and showed that the horizontal interface method would be more realistic than other interface methods. They included the horizontal interface in the calculation to the wetted perimeter 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 [16], Bousmar & Zech [3], Knight and Demetriou [11], Wright and Carstens[29], Knight and Shiono [13], Seckin [23], Patra et al. [19] Kejun Yang et al.[8], Khatua [10], Abril & Knight [18], Huttof et.al. [7]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. An attempt has been made to study the information on boundary shear distribution basing on which models on momentum transfer and stage-discharge relationship of compound channels are developed.

2 Experimental analyses

In the present work, a compound channel was fabricated using Perspex sheets inside a tilting flume in the Hydraulic Engineering Laboratory of the Civil Engineering Department, National Institute of Technology, Rourkela, India. The compound channel was symmetrical about the centerline of main channel making the total width of the compound section as 440 mm (Figure 1). The main channel was rectangular in cross section having 120 mm width and 120 mm at bank full depth. Longitudinal bed slope of the channel was taken as 0.0019. The roughness of the floodplain and main channel were identical. The bed roughness coefficient (Manning coefficient *n*) was estimated as 0.01 from experimental runs in the channel. A re-circulating system of water supply was established with pumping of water from an underground sump to an overhead tank from where water flow under gravity to the experimental channel through stilling chamber and baffle wall. A transition zone between stilling tank and the channel helped to reduce the turbulence of the flowing water. An adjustable tailgate at the downstream end of the flume was used to achieve uniform flow over the test reach in the channel for a given discharge. Water from the channel was collected in a volumetric tank that helped to measure the discharge rate. From the volumetric tank water was running back to the underground sump.

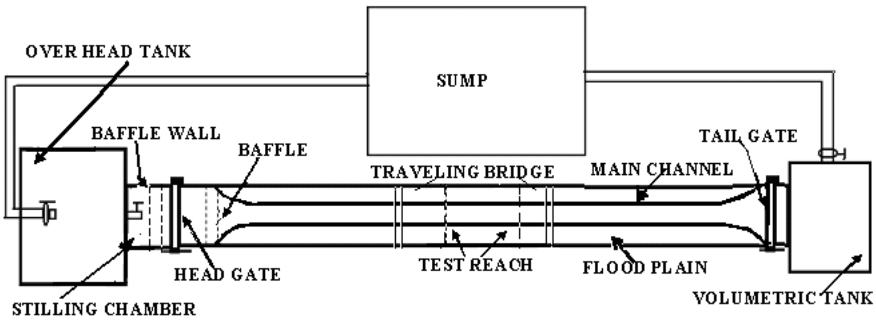

Figure 1 : Plan view of experimental set up of the compound channel

The measuring devices consisted of a point gauge mounted on a traversing mechanism to measure flow depths with least count of 0.1 mm. Point velocities were 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 was provided at the top of the experimental flume on which a traveling bridge was moved in the longitudinal direction of the entire channel. The point gauge and the micro-ADV attached to the traveling bridge could move both longitudinal and the transverse direction at the bridge position. Readings from the micro-ADV were recorded in a computer. As the ADV (down probe) was 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 were also used to measure velocity at some other points of the flow-grid. The Pitot tube was physically rotated with respect to the main stream direction till it recorded the maximum deflection of the manometer reading. A flow direction finder having a least count of 0.1° was 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 was noted by the circular scale and pointer arrangement attached to the flow direction meter.

h
H
Momentum Transfer
θ
θ
o

o
p
c
g

d
e
(1)
Floodplain
(3)
(2)
(2)
Main channel
a
a
(1)
Vertical interface plain
Diagonal interface
(3)
Horizontal interface plain
Floodplain
b
B

A total 21 numbers of stage-discharge data for both in-bank and over-bank flow conditions were observed at the test reach. Out of the 10 over-bank stage-discharge data, detailed velocity measurements for 5 stages were recorded at number of points at the pre defined grid points. 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 were evaluated from a semi log plot of velocity distribution. Boundary shear stresses were also obtained from the manometric readings of the head differences of Preston tube techniques using Patel's [17] relationship. Error adjustments to the shear value were done by comparing the corresponding shear values obtained from the energy gradient approach. The results so obtained by the two methods were found to be consistently within ±3% values. Summary of the discharges and

b_1 b_2

percentage of boundary shear in the floodplain (%S_{fp}) for different relative depths (β) observed from the experimental runs are given in Table 1.

Figure2: Interface Planes dividing a compound section into sub – sections

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

Ttest 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) range s = $(H-h)/H$
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
Present Channel	Type-I	0.0019	120	120	0	1	B/b = 3.667	8726-39071	0.118-0.461
Knight & Demetriou [14]	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	B/b = 4.0	185800-1103400	0.0504-0.499
	10	1.027×10 -3	1500	150	2.0	1	B/b = 4.4	236800-1093900	0.0508-0.464

3 Methodology

3.1. Shear force on the assumed interface planes

In Figure 2, the vertical, horizontal, and diagonal plains of separation of the compound channel are represented by the interface lengths o-g, o-o, and o-c respectively. Various boundary elements comprising the wetted parameters are labeled as (1), (2), (3) and (4). Label (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. Label (2) denotes floodplain beds of length (B – b), where B = total width of compound channel, and b = width or bed of main channel represented by label (4) Label (3) denotes the two main channel walls of length (2h). 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 (1) through (4).

Percentage of shear force carried by floodplains comprising elements (1) and (2) is represented as $\%S_{fp}$ and for the main channel comprising elements (3) and (4) is represented as $\%S_{mc}$.

Following Knight and Demetriou [11], Knight and Hamed [12] proposed an

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

(1)

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

$$= 48(\alpha - 0.8)^{0.289}(2\beta)^{m}\{1 + 1.02\sqrt{\beta}\,\mathrm{lo}$$

(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

$$m = 1/\left[0.75e^{0.38\alpha}\right]$$

(3)

For homogeneous roughness section (γ=1), equation (2) reduces to the form of Knight and Hamed [12] i.e. equation (1). Due to complexity of the empirical equations proposed by the previous investigators, a regression analysis was made

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

(4)

Once the shear force carried by the floodplain is known from equation (4), the momentum transfer in terms of apparent shear force acting on the imaginary interface of the compound section can be calculated. The analysis of momentum transfer helps in predicting the stage-discharge relationship of a compound channel, which is discussed in the later part of the paper. 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 originating from the main channel-floodplain junction must be equal to the resolved weight force along the main channel. It

$$\rho g A_{mc} S = \int_{mc} \tau\, dlp + ASF_{ip}$$

$$\int_{mc} \tau\, dlp$$

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, = 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

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

(6)

Figure 4: Variation of % error for calculating $\%S_{fp}$ with β for FCF data

$\%S_{fp}$

But since = 100 – ; and 100(ASF_{ip}/ρgAS) = percentage of shear force on the assumed interface, substituting the values, the apparent shear force on the

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

$\%S_{fp}$

in which $\%ASF_{ip}$ = percentage of shear force in the interface plane. Having computed using equation (2) or (4), it is easy to evaluate equation (7) for the assumed interface plane. 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 [22], Myers and Elsawy [16], Knight and Demetriou[11], Patra and Khatua[20]). 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 sub-sections for calculating discharge of compound channels by Divided Channel Method (DCM). 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.

4 Development of modified approach

4.1. Shear force along assumed interface planes in terms of angle Θ

Evaluation of apparent shear force at the imaginary interface is helpful for DCM to choose appropriate sub-division lines for separating a compound channel into sub-sections for discharge assessment. Based on the previous works, a general expression for momentum transfer across any interface plane in terms of the angle (θ□) made with the vertical line is derived. Consider an arbitrary interface (op), lying between extreme interfaces (oa) and (oe) which makes an angle θ to vertical line at the junctions (Figure 2). The convention, used for θ is 0o for vertical interface (og), positive if the interface lies in the main channel and negative, if the interface lies at the floodplain side. Two situations of locating interface plains can arise.

First, when interface (op) lies between (oa) to (oc) the ranges of angle θ, the expression for percentages of apparent shear force in the assumed interface is

$$SF_{ip} = 100\frac{(\delta - \beta^{2} \tan\theta)}{\delta\{1+(\alpha-1)\beta\}} - (100 - \%$$

(8)

where δ = aspect ratio of the main channel = b/h, α = width ratio and β = relative depth which are defined earlier. The second case is when interface op lies

$$ASF_{ip} = 100\left\{\frac{\delta\cot\theta - 4\beta + 4}{4\{1+(\alpha-1)\beta\}}\right\} - (100 - \%S$$

(9)

For any given interfaces lying between extreme interfaces oa and oe the angle θ is known so the equation (8) and (9) can be directly used to find easily the apparent shear along any interfaces. The equation is also helpful to plot the variation of apparent shear along interfaces to interfaces and flow depths to flow depths so as to find a suitable location of interfaces for accurate discharge prediction. For example, the percentages of apparent shear ($\%ASF_V$) for vertical interface (og) in Figure 6) is obtained by putting $\theta = 0^{o}$, in (9) and for diagonal interface, %ASFD is obtained by considering $\tan\theta = b/2h$ in (8) or (9)

5 Results and Discussions

Figure 6: Variation of apparent shear along various interface planes.

[SCM-Single Channel Method, Vee - (VDM-1), Vie - (VDM-1I), Hee - (HDM-1), Hie - (HDM-1I), Dee - DDM, Ma- Zero Shear Interface Method (ZSIM), AM- Area Method, VI - Variable Inclined Plain Method]

Figure 7: Variation of percentage of error discharge with relative depth by various approaches

Figure 1: **Figure 8: Error percentages between**

calculated and observed discharges for the FCF channel Myers & Brennan [21].

Using the present boundary shear stress distribution equation (13), the variation between the calculated $\%S_{fp}$ and observed values for all the ten types of compound channels are shown in Figure 5. In the same plot the variation of calculated $\%S_{fp}$ by previous investigators (i.e. equation 2 and equation 4) are also shown. The correlation statistics estimate indicates high correlations (R_2 = 0.98) when using the equation (**13**), than 0.68 and 0.74 respectively using equations (2) and (4). The standard error of estimate between observed and calculated values of %Sfp using the proposed model for the experimental channel are found to be minimum when compared to the previous models (Figure 5).

5.1. Shear force on the assumed interface planes for an angle Θ

Previous studies do not provide 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 in a compound channel. Keeping this in view, a series of experimental runs were conducted in the compound channel designed at NIT, Rourkela by varying depths ratio and using the derived equations (12) and (13). The results of momentum transfer across different interfaces of the experimental compound channel are shown in Figure 6. As can be seen, 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 (β = 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 (β = 0.406). This shows that apparent shear is higher at low floodplain depths and gradually reduces as depth over floodplain increases. Similar results are also obtained for horizontal and diagonal interface plane for the present channels as well as when global data sets are tested using the concept.

Using the derived equations (12) and (13) the momentum transfer at various interfaces each at 5^o intervals between the interfaces oa to oe are shown in Figure 6. The convention for momentum transfer is positive from the main channel to flood-plain and that from flood-plain to main channel is negative. It can be seen that while going from the interface plane *oa* to oe (Figure 6) the apparent shear stress gradually decreases from positive to negative value for all depths of flow over floodplain. Therefore in the present case, maximum positive momentum transfer takes place from main channel to floodplain if we consider the interface oa and the maximum negative momentum transfer from floodplain to main channel if we consider the interface oe. The interface plain of zero shear is located near the horizontal interfaces (approximately at $\theta = 99^o$) at β = 0.15 and for higher over-bank flow depths, the interface plane of zero shear is observed near a diagonal line of separation (approximately at θ= 40 ^{o}).

5. 3. Estimating discharge using different approaches

If Q_c is denoted as calculated discharge and Q_m as the measured discharge, the percentages of error and standard error for each series of experimental runs are computed using following equations:

$$rror(\%) = \frac{(Q_c - Q_m)}{Q_m} \times 1($$

(14)

where N = number of overbank flow observations for each compound channel geometry. Using common approaches, the error in discharge estimation for the experimental channel and a channels from the FCF series A are plotted in Figures 7 and 8 respectively. The notations used for various approaches as given in

$$\sqrt{(H-h)^2 + b^2}$$

As already stated, in DCM, 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 equal to (H-h) for vertical (say VDM-II), or (b) for horizontal (say HDM-1I), or for a diagonal interface 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 methods for such cases are termed as (say VDM-1, HDM-1 and DDM-1 respectively.

Single channel method (curve SCM) is found to give higher discharge error for lower over-bank flow depths and very less error for high over-bank flow depth which is in line with the findings of Seckin [23]. These also show that at very high overbank depths, the compound channel behaves like a single unit (Bhowmik and Demissie[2]). SCM also gives the maximum point error [e.g. for α = 6.67 discharge error is more than 45% (Figures 8). Smilarly, VDM-II (curve Vie) gives better discharge results than VDM-I (curve Vee) which is in line with the findings of Mohaghegh and Kouchakzadeh [15]. VDM-1 (curve Vee) provides higher error for compound channels of wider floodplain (e.g. α = 6.67 of Figure 8). For all the compound channels studied, the error results from HDM-I (curve Hee) is less than that from HDM-II (i.e curve Hie) which is in line with the findings of Seckin[23]. It is again observed that HDM-I approach gives better discharge results than the corresponding vertical interface method (VDM-I) for low depths of flow over floodplain but gives large discharge error at higher depths. These findings are similar to the results of Mohaghegh and Kouchakzadeh [15]. It is also noticed that, DDM (curve Dee) gives less error (Figure 7 and 8) than all the VDM and HDM for all the compound channels studied. This finding follows the results of Wormleaton et. al. [37]; Knight and Hamed [15], Khatua [12] and Seckin [29] etc. Both the Area method (curve AM) and the variable inclined plain method (curve VI) gives higher standard error for compound channels of wider floodplains (e.g FCF Series-A channels, Figure 8).

Basing on the present analysis, it can be concluded that both HDM-1 and DDM are good approaches. HDM-1 is better for low overbank depth and DDM is better for higher overbank depths.

6 Conclusions

The following conclusions can be drawn from the above investigation

- For a compound channels the important parameters affecting 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 present formulations for estimating the percentages of shear force carried by floodplain boundary $\%S_{fp}$ has the distinct improvement when compared to the previous investigators in the sense that it is quite adequate for all types of straight compound channel geometry (narrow as well as wide flood plain channels). Proposed equations by the previous investigators gives $\%S_{fp}$ more than 100 % when applied to a compound channel of wider floodplains (i.e. width ratio α > 10).

- Using the boundary shear distribution results, the momentum transfer at different interfaces originating from the main channel and floodplain junction for all types of geometry are quantified. The proposed equation provides the estimation of apparent shear stress for any assumed interface in terms of an angle θ it makes with the vertical line. 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.

- Basing on the present analysis using DCM, it can be concluded that both HDM-1 and DDM are better than other approaches. HDM-1 is better for low overbank depth and DDM is better for higher overbank depth. The adequacy of the developed equation for shear stress distribution along the boundary of compound channels are verified using the data from present channel, FCF-A channels.

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