Apparent shear in an asymmetric compound channel

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ABSTRACT: For uniform flow conditions in a compound open channel, much of the hydraulic resistance may be ascribed to channel roughness and flow characteristics with further accounting for other forces. The resistance to flow along the boundary of the compound channel is exhibited in the form of shear stress along the periphery, known as boundary shear. Distribution of this boundary shear across the lateral direction of the compound channel is one of the challenging tasks. An expression to predict this boundary shear distribution is presented depending on geometric and hydraulic parameters. The performance of the model is found to give better results as compared to models of other investigators when applied to experimental data and FCF data. Three phenomenological generalized expressions are also presented and applied to asymmetric compound channels of various geometric and hydraulic parameters for delivering the apparent shear at any possible interface. The consequence of the approach for predicting the apparent shear is analyzed through an experimental investigation concerning the boundary shear distribution in asymmetrical compound channels of different width ratio and flow conditions. Moreover, the current approaches are also capable of evaluating the intensity of momentum transfer across different interfaces and locating the zero shear interfaces for prediction of discharge by area method of reasonable accuracy.

1 INTRODUCTION

Compound channels have major area which remains in predicting the discharge carrying capacity of a channel when flooded. During flood event, a part of the river discharge is carried by main river channel and the rest part is carried by one or two side flood plain. If the compound section has one side flood plain, it is known as asymmetric compound section otherwise it is symmetrical or unsymmetrical one. For symmetric and unsymmetrical cases, both adjacent flood plains carry the discharge but for asymmetric cases, a single flood plain carries the rest major part of the flow during flood. Usually the velocity of main channel is faster than that of flood plain. When this two faster and slower moving fluid interacts, exchange of mass and momentum occurs at the transition of main channel and flood plain making the flow prediction difficult. Many researchers demonstrated that momentum transfer phenomenonis responsible for the non-uniformity of depth averaged velocity and boundary shear distribution across the section perimeter making prediction of flow variables more difficult(Zhelenyacov,1965, Ghosh and Jena, 1971, Knight and Hamed, 1984, Khatua and Patra, 2012).

Boundary shear distribution of an open channel flow helps to understand the resistance relationship, to check the stability of bed material, design of stable channels and construction of retaining wall. Distribution of this parameter mainly depends on the shape of the cross sectional geometry and secondary flow structures. Higher secondary flow due to momentum transfer leads to the variation of local shear stress distribution from point to point along the wetted perimeter causing increase of flood plain shear and decrease the main channel shear. (e.g., Rajaratnam and Ahmadi, 1979, Myers R.C. &Elsawy, 1975). Research on this has been made generally for symmetrical and unsymmetrical compound channels and very limited work has been done on asymmetrical compound channels.

Many investigators developed relation for distribution of boundary shear stress in compound channel. Knight and Demetriou, 1983 worked on distribution of shear stress of compound channel. Then following this, Knight and Hamed, 1984 developed a relation for discharge assessment of smaller width ratio. Khatua and Patra, 2007 developed a model for width ratio of 5.57 which fails to give percentage shear force distribution on flood plain ($\%S_{fp}$)of Flood channel facility (FCF Series A) data. These three models were noticed to estimate unrealistic value with significant error for channels greater than 10 (Khatua et al, 2011). Improving these models Khatua et al, 2011developed a relationship of $\%S_{fp}$with percentage area of flood plain ($\%A_{fp}$)taking more experimental data sets. Then Mohanty et al, 2013 observed that these above relationship fail to work for some rivers of higher width ratio. So they developed a new relationship for compound channels of higher width ratios of 12. Most of the approaches are suitable for symmetrical compound channel only. As compared to symmetrical compound channel, stronger interaction takes place at the junction of main channel and flood plain of asymmetrical compound channel. So these methods are not suitable to predict $\%S_{fp}$for asymmetric flood plain cases andeven noticed to give maximum error more than 50% for discharge assessment. A new relationship for predicting boundary shear distribution in terms of percentage shear on flood plain ($\%S_{fp}$) of asymmetrical compound channel has been developed by considering the wide ranges of width ratio $2.7 \leq \alpha \leq 12$ and relative depth $0.10 \leq \beta \leq 0.50$so thatthe proper distribution of boundary shear can be effectively estimated. Where $\alpha = B\ /\ b$, $\beta = (H - h)/H$and $\delta = b\ /\ h$, B = Total width of the compound channel, b = bottom width of the main channel, H = Depth of flow over main channel and h=bank full depth. Proper distributions of boundary shear stress in main channel and flood plain are also helpful for evaluating apparent shear which indirectly help to predict the stage discharge relationship for compound channel. Knowledge of momentum transfer in terms of apparent shear helps to decide a suitable divided channel method to predict the stage discharge relationship of a compound channel flow. Generalised expressions to estimate the apparent shear at different interface have been presented. This will help for accurate stage discharge prediction in a compound channel with both symmetric and asymmetric flood plains.

2 EXPERIMENTAL DETAILS

In this part of study, experimental results of compound channels with asymmetric flood plain for three different configurations are described. These channels are constructed using neat finished plain cement concrete at the hydraulic engineering laboratory of the Civil Engineering Department, National Institute of Technology, Rourkela, India. Flood plains are at right side making the total width of the compound sections 168cm, 145 and 119 respectively with varying width ratio (Figure.1and 2). The main channels are trapezoidal in cross section with 1:1 side slope having 33cm bottom width and 11cm at bank full depth. The longitudinal bed slope is found to be 0.001 satisfying subcritical flow conditions. The roughness of the flood plain and main channel are kept same having Manning's *n* is equal to 0.01 by which the effect of asymmetric geometry of the flood plain on assessing different flow variables can be studied. Water was supplied through numbers of centrifugal pumps discharging into large overhead tanks. Water is made to flow to the stilling tank of flume from the overhead tank by regulating valves. Baffle walls arrangement have been made inside the stilling basin to reduce the turbulence. Water is made to flow under gravity from the head gate end to the tail gate of the flume under uniform and steady flow conditions. At the downstream end there is a measuring volumetric tank followed by a large underground sump which feed the water to the overhead tank through pumping. This is an arrangement of complete recirculation system of water for the experimental channels.

Boundary shear measurements have been performed by standard Prandtl type Micro-Pitot tube in conjunction with a manometer of accuracy 0.12 mm at the desired locations. Error adjustments to the boundary shear value are done by comparing the corresponding boundary shear values obtained from the energy gradient approach. The results so obtained by the two methods are found to be consistently within ±3% values. The flow rate were measured through a rectangular notch fitted near the tail gate of the flume. The notch has been pre calibrated by measuring the flow rate of the water passing through a volumetric tank by time rise method. Point gauge with least count 0.01 cm is used to measure the water surface elevation above the bed of main channel. Plan view and sectional view of all the experimental channels and FCF channels have been shown in Figure.1 and Figure.2 respectively. To assess more clearly the dependency of other geometrical parameters such as aspect ratio and width ratio , the second series of data have been chosen from the large scale compound channel facility i.e., the Flood Channel Facility, UK which has smaller width ratio (α=2.7), located at the laboratories of HR Wallingford Ltd shown in Figure 1. The details of geometric and hydraulic parameters of the experimental data sets have been tabulated in table 1.

Table 1. Geometric and hydraulic parameters of experimental data sets

All Series	Bed Width h(m)	Bank full Depth (m)	Side Slope	Bed Slope	Relative Depth	Aspect Ratio	Width Ratio	Mann-ing's *n*
NITR 1	0.33	0.11	01:01	0.001	0.10-0.45	3	5.1	0.01
NITR 2	0.33	0.11	01:01	0.001	0.10-0.35	3	4.4	0.01
NITR 3	0.33	0.11	01:01	0.001	0.10-0.40	3	3.6	0.01
FCF-6	1.5	0.15	01:01	0.001027	0.05-0.5	10	2.7	0.01
River Trent	15.4	2.1	01:5.2	0.001	0.032-0.12	7.33	5.14	0.032 & 0.015

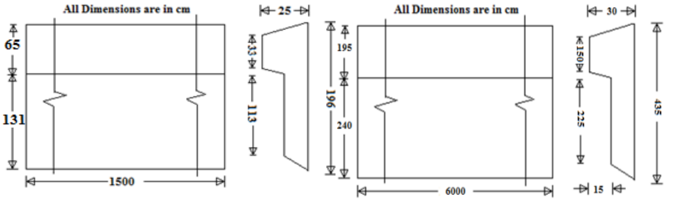


Figure 1.Plan and sectional View of Experimental asymmetrical compound channels of NITR-5.1 and FCF Series 6

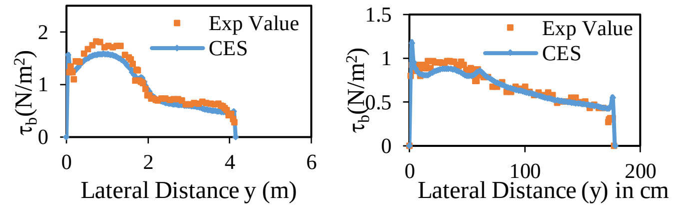
Figure 2. (a) Photograph asymmetrical compound Channels fitted with instruments (NITR-5.1) (b) compoundchannel ofFlood Channel Facility at H.R. Wallingford (Knight and Shiono 1990)

2.1 *Shear force results*

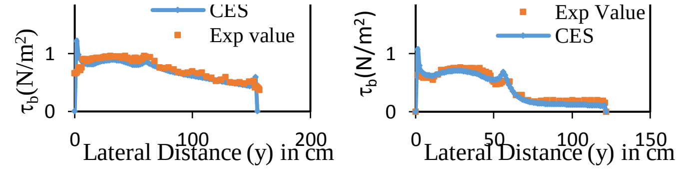
The lateral exchange of momentum between main channel and flood plain at the junction magnificently affects the shear stress distribution. Boundary shear force resulted from the experiment on each subsection of the wetted perimeter were numerically integrated to give the mean boundary shear and the mean shear force in the sub sections. From the boundary shear force distribution, a brief idea regarding the transfer of momentum to different interfaces can be acquired. As the channels are with asymmetric flood plains, the shear values differ largely due to the strong interaction at the junction. The wetted perimeter of the compound channel is divided into four parts i.e., the flood plain side slope region, the flood plain bed, the main channel side slope and main channel bed.

The boundary shear distribution for a typical depth of the FCF asymmetric compound channel -Series 6 has been plotted in the Figure 3a. The boundary shear distributions for the present three experimental asymmetric compound channels for five flow depths in each channel have been evaluated. Boundary shear distributionfor three typical flow depths i.e. one from each channel, has been demonstrated in Figure 3 b,c,d respectively. The boundary shear stress measurements along the wetted perimeter of a compound channel for different flow depths and for different geometry are tedious.

Further there are very limited data sets available regarding the boundary shear stress distributions in asymmetric compound channels. As our prime aim is to develop a generalized mathematical model to predict the apparent shear stress in an asymmetric compound channel, which in turns depend upon the boundary shear stress distribution therefore an attempt has been made to extract the boundary shear stress distribution by an alternate but reliable approach. Shiono and Knight (1989) have proposed a numerical method popularly named as SKM method for accurately predicting boundary shear distribution in a compound channel. The method is widely and trustily used worldwide in the form of software known as Conveyance Estimation System (CES, Wallingford, UK).



(a)Width ratio=2.7(H=0.19793m) (b)Width ratio=5.1, (H=0.16m)



(c)Width ratio=4.4, (H=0.16m) (d)Width ratio=3.6(H=0.12m)

Figure 3. Lateral distribution of the depth averaged boundary shear stress (τ_b) for (a)FCF Series 6, (b)NITR Series 5.1,(c)NITR Series 4.4 and (d)NITR Series 3.6 for some typical flow depth

CES is a standard quasi 2-D research tool developed by joint agency/DEFRA Research program and extensively recommended for prediction of discharge. CES adopts the Reynolds-Averaged Navier-Stokes (RANS) approach simplified by (Shiono and Knight, 1990) known as SKM method to produce the lateral depth averaged velocity distribution, boundary shear distribution, friction velocity and discharge for different channels with varying width ratio and relative flow depths. The basic form of depth-integration of the RANS equations for flow in stream wise direction presented by Shiono& Knight (1988) is

$$\rho\frac{\partial H(\overline{UV})_d}{\partial y} = \rho H g S_0 - \beta'\tau_b + \frac{\partial\left(H\overline{\tau_{yx}}\right)_d}{\partial y} \qquad (1)$$

Where ρ =water density (kg/m^3); g= Acceleration due to gravity, H = Depth of flow over main channel, x=Stream wise direction parallel to bed(m), y= lateral distance across section (m),U_d = depth average stream wise velocity (m/sec), V_d = depth average lateral velocity (m/sec), τ_b = bed shear stress (N/m^2),τ_{yx}= Reynolds stress(N/m^2), β'= Coefficient for influence of lateral bed slope(S_y) on the bed shear stress and S_0= bed slope. Shiono and Knight (1990) further simplified equation (1) as

$$\rho\frac{\partial H(\overline{UV})_d}{\partial y} = \rho H g S_0 + \frac{\partial}{\partial y}\left(\rho\lambda H^2\left(\frac{f}{8}\right)^{\frac{1}{2}} U_d\frac{\partial U_d}{\partial y}\right) - \frac{\rho f\beta' {U_d}^2}{8} \text{(2a)}$$

The other form of the equation is obtained by simplifying (1) for unit flow rate (q in m2/sec) can be rewritten as (Samuels, 1989)

$$\frac{\partial}{\partial y}\frac{\left(\overline{q_x q_y}\right)_d}{H} = H g S_0 + \frac{\partial}{\partial y}\left(\lambda H\left(\frac{f}{8}\right)^{\frac{1}{2}} q_x\frac{\partial}{\partial y}\left(\frac{q_x}{H}\right)\right) - \frac{f\beta' {q_x}^2}{8H^2} \quad \text{(2b)}$$

The analytical solution for equation 2 has been implemented in this software whereby the channel cross section is discretized into a number of flow elements. The resulting system of equations is solved to find the local depth averaged velocity and boundary shear stress within each element.Accuracy of the numerical approach by CES for FCF-6 and NITR channels for all flow depths to predict the boundary shear distribution have also been tested before extracting data sets. Comparison of the results for some typical flow depths are presented in Figure (3). CES has been found to evaluate the boundary shear distribution more accurately with mean average error less than 5% for all flow depths of these channels. Though CES is found to under predict the shear distribution uniformly along the wetted perimeters of the compound channel, the percentage of shear in the subsections almost remain unchanged as compared to the distribution estimated by the measured value.As the present experimentation in NIT asymmetric compound channel bears width ratio of 5.1, 4.4 and 3.6 respectively and FCF channel bears single width ratio of 2.7 so a wide range of data sets of various width ratio of 6,7,8,9,10,11 and 12 have been generated usingCES software. Details of geometric and hydraulic parameters of the extracted data sets have been tabulated in table 2.

Table 2.The geometrical and flow parameters of thechannels generated from CES software

Series	Main Channel		Depth of flow (*H*)	Side Slope (*n*)	Bed Slope (S_0)	Relative Depth (β)	Aspect Ratio (δ)	Width Ratio (α)
	Bed Width(*b*)	Bank full Depth(*h*)						
Type1 (Trapezoidal)	1.5	0.15	0.16,0.18 0.21,0.25 0.3	1:1	0.001027	0.1,0.2, 0.3,0.4 0.5	10	6,8,10 12
Type2 (Trapezoidal)	0.33	0.11	0.12,0.13 0.15,0.18 0.22	1:1	0.001238	0.1,0.2, 0.3,0.4 0.5	3	7,9,11

3 DEVELOPMENT OF BOUNDARY SHEAR DISTRIBUTION MODEL

The boundary shear distribution for asymmetrical compound channel is found to be much different as compared to that for symmetrical one. The equations developed by previous investigators are generally meant for symmetric compound channel as described earlier. Figure 4 shows the boundary elements of an asymmetrical compound channel. Boundary elements from *a*to *e* comprising the wetted perimeter denotes inclined main channel wall of length $\sqrt{2}H$, bed width of channel *b*, smaller main channel of length $\sqrt{2}h$, flood plain of width b_f, flood plain wall of inclined length $\sqrt{2}(H-h)$. Shear stress distribution at each point of the wetted perimeter is numerically integrated over the respective sub lengths of each boundary elements to obtain the respective boundary shear force per unit length for each element. Then the total shear force per wetted perimeter of the channel gives the sum of boundary shear forces of all the elements. This is resisted by the whole compound channel which is used as a divisor when calculating percentage shear carried by flood plain $\%S_{fp}$ or other boundary elements.

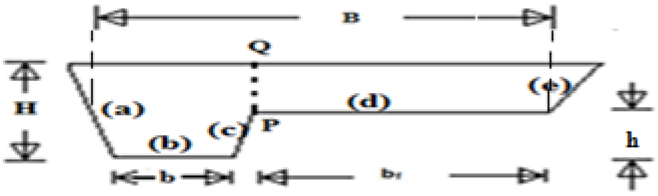


Figure.4 Schematic Cross Section of Present NITR Asymmetrical Channel

Some previous investigators have developed equations for $\%S_{fp}$ which are listed below.

1.Knight and Demetriou (1983)

$$\%S_{fp} = 48(\alpha - 0.8)^{0.289}(2\beta)^{m} \qquad (3a)$$

2. Knight and Hamed (1984)

$$\%S_{fp} = 48(\alpha - 0.8)^{0.289}(2\beta)^{m}\{1 + 1.02\sqrt{\beta}log\gamma\} \qquad (3b)$$

The exponent m can be evaluated from the relation

$$m = {}^{1}/_{[0.75e^{0.38\alpha}]} \qquad (3c)$$

$\gamma$is the ratio of roughness between flood plain and main channel.

3.Khatua and Patra (2007)

$$\%S_{fp} = 1.23(\beta)^{0.1833}(38Ln\alpha + 3.6262)\{1 + 1.02\sqrt{\beta}log\gamma\} \qquad (3d)$$

4.Khatua et al. (2012)

$$\%S_{fp} = 4.1045\left(\frac{100\beta(\alpha-1)}{1+\beta(\alpha-1)}\right)^{0.6917} \qquad (3e)$$

5. Mohanty et al. (2013)

$$\%S_{fp} = 3.3254\left(\frac{100\,\{\beta\alpha\delta-\beta(\delta+2s)\}}{\beta\alpha\delta+(1-\beta)(\delta+s)}\right)^{0.7467}\{1 + 1.02\sqrt{\beta}log\gamma\} \qquad (3f)$$

Equations developed by previous investigators are well fitting to symmetric compound channels only. Keeping these points in view, this research has been extended to develop a generalised equation to predict boundary shear distribution for an asymmetrical compound channel of different geometry and flow conditions. For this purpose, experimental investigations have been done and more data sets have been collected from literatures. Additional data sets have also been extracted utilising CES software. Therefore for an asymmetrical compound channel, this research used wide ranges of width ratio (α =2.7-12) and relative flow depth (β =0.1-0.5). Many previous investigators reported that there is a close relationship lies between $\%S_{fp}$and $\%A_{fp}$. So a generalised relationship between $\%S_{fp}$ and $\%A_{fp}$ has been developed with high regression coefficient of R^2 =0.99 and graphically demonstrated in Figure 5. The percentage area of flood plain $(\%A_{fp})$ is simplified withvarious geometric and hydraulic parameters as presented in equation (4)

$$\%S_{fp} = 3.576\left\{\frac{100\beta\left(\alpha-1-\frac{2.5n}{\delta}+\frac{0.5n}{\delta^*}\right)}{\left(1+\frac{n}{\delta^*}\right)+\beta\left(\alpha-1-\frac{2n}{\delta}\right)}\right\}^{0.717} \qquad (4)$$

Where width ratio $(\alpha) = (B\ /\ b)$, relative flow depth $(\beta) = (H-h)/H$, main channel aspect ratio $(\delta) = (b\ /\ h)$, flow aspect ratio $(\delta^*) = b\ /\ H$, B = Total width, b = bottom width of main channel H = Depth of flow over main channel, h=bank full depth and if (V:H::1:n) n=side slope of main channel.

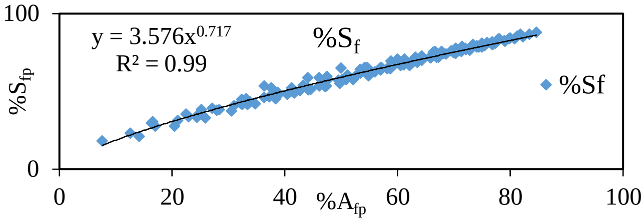


Figure 5.Variation of $\%S_{fp}$ with Area ratio $(\%A_{fp})$

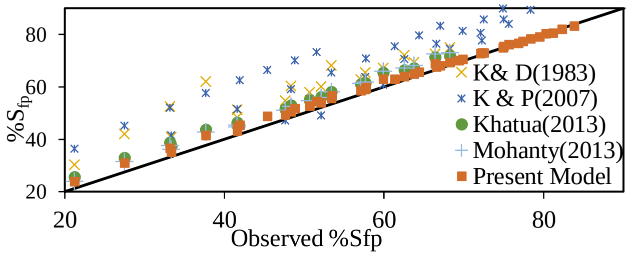


Figure 6. Comparison of observed $\%S_{fp}$ with Predicted $\%S_{fp}$

Using the proposed method along with the models of other researchers i.e., Knight and Demetriou (1983), Khatua et al. (2007), Khatua et al. (2012) and Mohanty et al.(2013), the $\%S_{fp}$ have been estimated for all experimental channels and all data sets extracted from CES. In first stage, model results i.e., Comparison of Predicted $\%S_{fp}$ Vs observed $\%S_{fp}$ with for various models have been compared graphically in the Figure.6. The efficacy of the developed equation (Equation 4) has been clearly seen when expression is compared with other models as demonstrated in Figure 6.

4 APPARENT SHEAR FORCE IN VARIOUS INTERFACES

For any regular prismatic channel, the total resolved weight force along main channel must be equal to sum of boundary shear force acting on the main channel bank and bed with an apparent shear force acting on interface mathematically presented as

$$\rho g A_{mc} S = \int \tau dp + ASF_{ip} \text{ or } ASF_{ip} = \rho g A_{mc} S - \int \tau dp \quad (5)$$

In which ρ= density of fluid g=acceleration due to gravity, S= slope of the energy line, A_{mc}=area of the main channel,τ=shear stress on the surface of the main channel. Apparent shear force can be manifested in the form of interaction length at the interface while calculating discharge (Q) using divided channel method (DCM). So the proper quantification of main channel perimeter to be increased to a length (X_{mc}) needs to be selected to account the net dragging force. Similarly, the wetted perimeter of the flood plain is suitably decreased with an acceptable length X_{fp} considering the accelerating force on the flood plain due to pulling of main channel water. For any assumed interface, $X_{mc}\tau_{mc}$ or $-X_{fp}\tau_{fp}$ is taken as the apparent shear force ASF_{ip} at that interface (Khatua et.al 2012). So a generalized term for X_{mc} and X_{fp} can be written as

$$X_{mc} = P_{mc}\left[\frac{100}{100-\%S_{fp}}\frac{A_{m\theta}}{A} - 1\right], \& X_{fp} = P_{fp}\left[\frac{100}{\%S_{fp}}\left(\frac{A_{m\theta}}{A} - 1\right) + 1\right] (6)$$

Figure.6a and Figure. 6b represents different possible interfaces originating from the junction between the main channel and floodplains. The point o is the junction point, a is the extreme left point on the floodplain with water surface, g is the vertical interface point with water surface, c is the extreme right point of the flood plain with water surface, f is the horizontal interface meeting point and e is the extreme right bottom of main channel. The lines oa and oe are the extreme cases of assumed interface plain that can be used to separate an asymmetrical compound section into subsections for discharge estimations. The line op is the any interface between oe to oe.

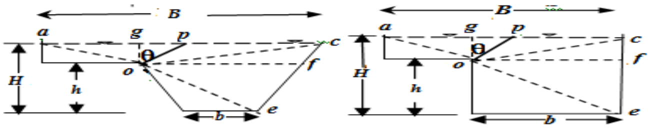


Figure 6(a,b) .Interface planes in an asymmetric compound channel with trapezoidal main channel and rectangular main channel

To estimate the discharge accurately, DCM can be applied with inclusion of X_{mc} to the main channel wetted perimeter and subtraction of X_{fp} from the flood plain wetted perimeter. By multiplying $100\frac{\tau_{mc}}{\rho gAS}$ to X_{mc} or $100\frac{\tau_{fp}}{\rho gAS}$ to X_{fp} the percentage of apparent shear force in an interface is obtained. Where τ_{mc} and τ_{fp} are the average boundary shear stress in main channel and floodplain respectively. Apparent shear stress(τ_{ai}) at any interface can be expressed as

$$\tau_{ai} = \frac{\tau_{mc}X_{mc}}{X} = \frac{(100-\%S_{fp})\rho gAS}{100P_{mc}}\frac{X_{mc}}{X} \qquad (7)$$

Where X= Actual interface length, e.g., for vertical interface $X = (H-h)$(og in Figure 6) and for horizontal interface it will be top width the main channel (of in Figure 6). Many existing open channel softwares like HEC-RAS, ISIS, HYDRO-1D and MIKE11 etc. adopt DCM approach by subdividing the whole compound section vertically, horizontally or diagonally for discharge assessment. Later it is perceived that these approaches provide poor quality output due to the exclusion of proper interacting length. Looking to this point in view generalised expressions for estimating the apparent shear force at various interfaces have been derived. Three ranges of possible interfaces (*oa* to *oc*, *oc* to *of* and *of* to *oe*) have been chosen and the generalised expressions to find the percentage apparent shear force($\%ASF_\theta$) in terms of geometric and hydraulic parameter at any interfaces for trapezoidal cross sections having *V*:*H*::*1*:*n* side slope are derived as

Case1 The interface lies between *oa* and *oc* (Figure.6a, b)

$$\%ASF_\theta = \frac{100\tau_{mc}P_{mc}}{\rho gAS}\left[\frac{100\{\delta(\delta^*+n)-0.5\beta(n+\tan\theta)(\delta-\delta^*)\}}{(100-\%S_{fp})\{\delta(\delta^*+n)+(\alpha\delta-\delta-2n)\beta\delta^*\}}-1\right] \quad (7a)$$

Case2 The interface lies between *oc* and *of* (Figure.6a, b)

$$\%ASF_\theta = \frac{100\tau_{mc}P_{mc}}{\rho gAS}\left[\frac{100[\{\delta+n+0.5(\delta+2n)^2(n\cot^2\theta+\cot\theta)\}\delta^*(1-\beta)]}{(100-\%S_{fp})\{\delta(\delta^*+n)+\beta\delta^*(\alpha\delta-\delta-2n)\}}-1\right] \quad (7b)$$

Case3 The interface lies between *of* and *oe* (Figure.6a, b)

$$\%ASF_\theta = \frac{100\tau_{mc}P_{mc}}{\rho gAS}\left[\frac{100[\{\delta+n+0.5\cot\theta(\delta+n)(\delta+2n)\}\delta^*(1-\beta)]}{(100-\%S_{fp})\{\delta(\delta^*+n)+\beta\delta^*(\alpha\delta-\delta-2n)\}}-1\right] \quad (7c)$$

The quantity of apparent shear in terms of apparent shear length (X_{mc}) for the three channels of FCF-6, NITR (5.1) and river Trent are estimated and demonstrated in Figure 7(a), (b) and (c) respectively.

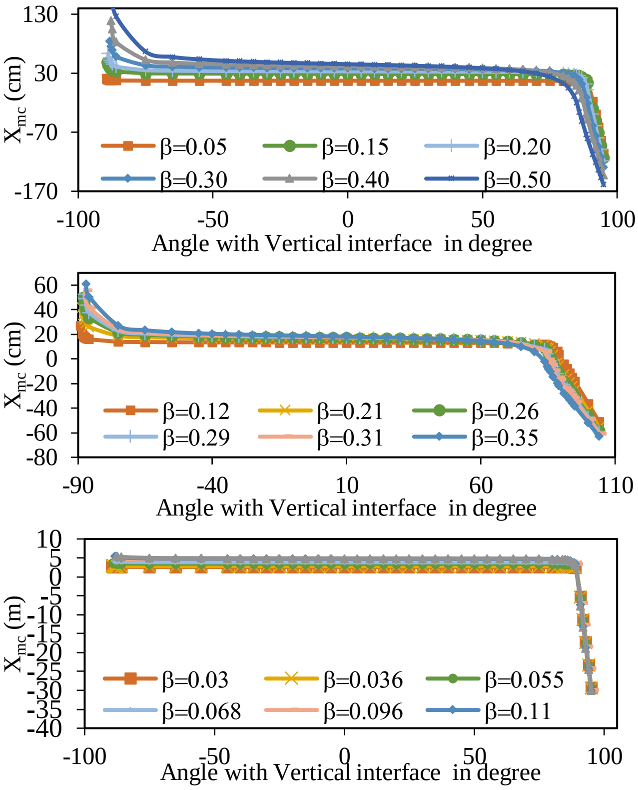


Figure 7. Variation of apparent shear length along various plane of separation (a) FCF6 (b) NITR (5.1) and (c) River Trent

4.1 *Discharge Estimation*

Carrying capacity for two experimental compounds channels (NITR 5.1 and FCF-6) are estimated through single channel method (SCM) and divided channel method (DCM). To test the consistency of these prediction models, the River Trent data were also utilised herein. Further more comparisons of the traditional model i.e., divided channel method (VDM, HDM and DDM) consisting of vertical, horizontal and diagonal division lines with interface length excluded and included (named as EVDM, EHDM, EDDM for excluding cases and IVDM, IHDM, IDDM for including cases) have been considered. To get a repeatable comparison of the efficiencies of these methods mean absolute percentage error (MAPE), has also been computed as per the following equation.

$$\text{MAPE} = \frac{1}{n}\sum 100\frac{|Q_{computed}-Q_{measured}|}{Q_{measured}}$$

4.2 *Observations*

For an assumed interface (*op* in Figure 3), if the apparent shear in terms of interaction length is zero or negligible then the excluded DCM (i.e., dividing the compound channel into two parts with *op* as the interface) will provide good discharge results. Here no inclusion of interacting length is required. Then the corresponding DCM can be named as zero shear area method for that geometry and flow conditions. For example in case of vertical interface ($\theta = 0^0$) or horizontal interface ($\theta=90^0$), if the apparent shear in terms of interaction length is found to be zero or negligible then the corresponding excluded vertical division method (EVDM) or excluded horizontal division method (EHDM) will provide better discharge results as compared to other DCMs.

Further if the apparent shear stress in an assumed interface (*op* in Figure 3), is equal to the boundary shear stress of the main channel then there is a need of addition of total interface lengthto the wetted perimeters of the main channel to compensate the momentum transfer for the assessment of discharge. For example in case of vertical interface ($\theta=0^0$) or horizontal interface ($\theta=90^0$), if the average apparent shear stress (in terms of interaction length X_{mc})is found to be same as the interface length *X*, then average apparent shear stress ($\boldsymbol{\tau_{ai}}$) is equal to average boundary shear stress of the main channel ($\boldsymbol{\tau_{mc}}$**).** In other words we can say that for any interface when$\boldsymbol{\tau_{ai}} = \boldsymbol{\tau_{mc}}$ then the corresponding included vertical division method (IVDM) or included horizontal division method (IHDM) will provide better discharge results as compared to other DCMs. The applicability of the equation 7 has been verified with the following results from FCF data set and NITR channel data set.

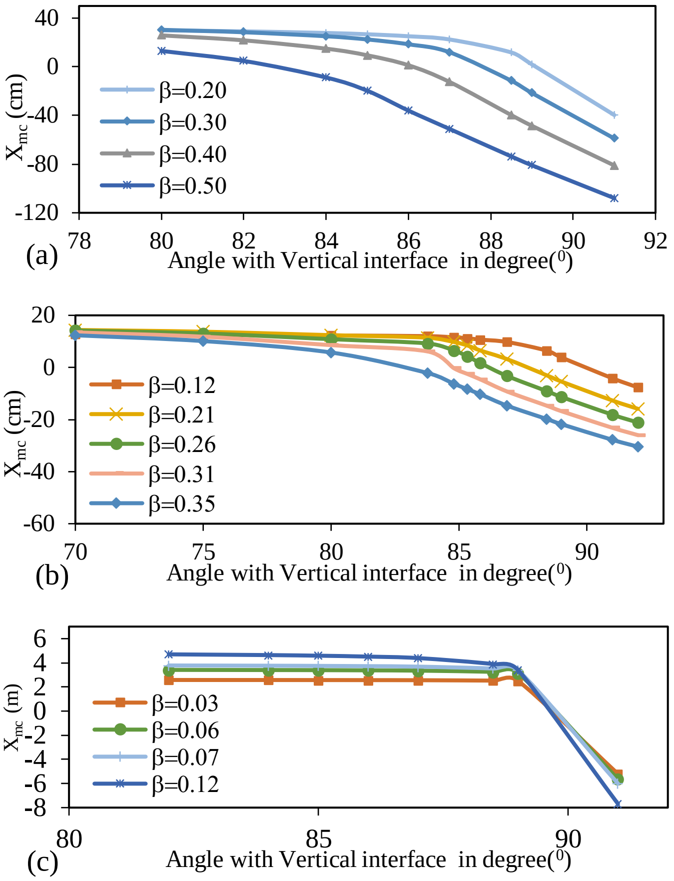


Figure 8. Variation of apparent shear length along various plane of separation (a) FCF6 (b) NITR (5.1) and (c) River Trent

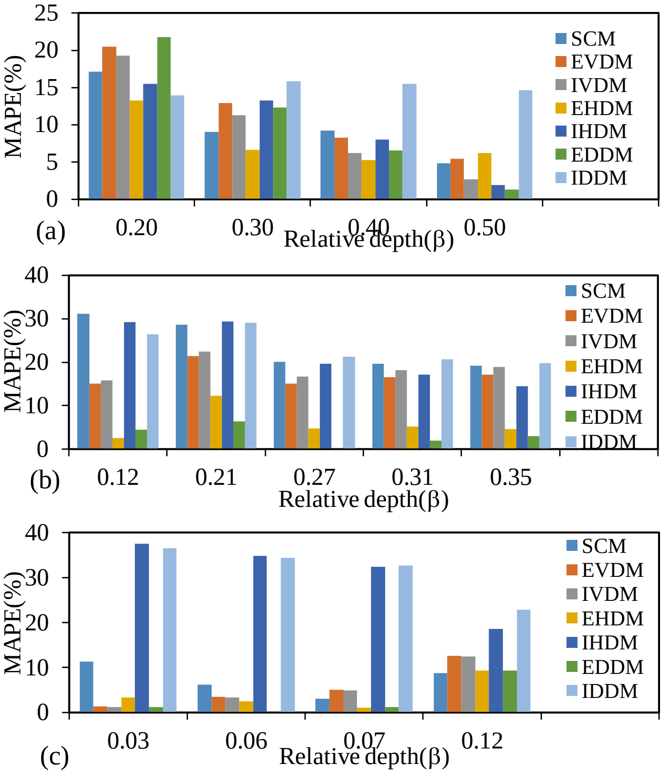


Figure 9. Comparison of different discharge prediction methods for (a) FCF6 (b) NITR (5.1) and (c) River Trent

The best predictable approach for discharge assessment for a specific geometry and flow condition has been distinguished to proof the applicability. For understanding it more effectively, a certain portion (zoom of Figure 7) of some typical depths of the experimental channels (FCF-6 and NITR 5.1) and river Trent have been presented in Figure 8.Interacting lengths(X_{mc}) are considered for that portions where X_{mc} changes its sign and becomes zero in between. The positive sign indicates the transfer of momentum from main channel to flood plain and vice-versa. When magnitude is zero that means it is the suitable interface without momentum transfer and can be chosen as the perfect interface where DCM can be applied.

In Figure 8 (a) representing the channel of FCF-6, the value of X_{mc} for the high relative depth ($\beta = 0.50$) is zero occurring between θ = 82^0 to 84^0 that provides a clear indication of choosing the excluded diagonal division method (EDDM) for reasonable discharge assessment. From Figure 9 (a), it can clearly be revealed that EDDM agrees very well for $\beta = 0.50$. However, for other relative flow depths ($i.e., \beta = 0.20, 0.30, 0.40$), it can be noticed from Figure 8 (a) that the value of X_{mc} become zero for θ closer to 90^0. This finding shows that the EHDM can predict discharge for those flow depths with great accuracy which can also be found from Figure 9 (a). Similarly for the NITR channel, $X_{mc}$for the smallest relative flow depth ($\beta = 0.12$) crosses the zero value at θ =90^0 (Figure 8 b). So the precise method for discharge estimation can be adopted through EHDM and the same finding can also noticed in Figure 9(b) i.e., EHDM gives negligible discharge error of around 2%. Identical results have been perceived for the river Trent (Figure 8c) and for all the channels. As for all relative flow depths, the value of apparent shear stress in terms of (X_{mc}) crosses the zero line closer to θ = 90^0. EVDM and EHDM predict better for all flow depths which is observedinFigure 9(c). It is realised from above results that EHDM appears as the good predicting approach for lower relative flow depth and EDDM for higher relative flow depth.

5 CONCLUSIONS AND FUTURE WORK

1. An experimental investigation concerning the measurement of boundary shear along the wetted perimeter of asymmetrical compound channels of three aspect ratio have been done. The conveyance estimation system (CES) software, based on SKM has been used to generate more datasets on boundary shear distribution with mean average error less than 5%. CES is found to over predict the shear distribution uniformly along the total wetted perimeters, however the percentage of shear in the subsections remains almost unchanged as compared to the distribution estimated by the measured value.
2. A generalised model for percentage of shear force carried by the flood plain ($\%S_{fp}$)for asymmetriccompound channelhas been proposed

in terms of width ratio, relative flow depth, main channel aspect ratio and flow aspect ratio. The strength of the expression has been compared well with models of other investigators.

3. To identify a suitable interface of DCM for establishing accurate stage –discharge relationship, three ranges of possible interfaces have been derived and the generalised expressions to find the percentage apparent shear force($\%\mathrm{ASF}_\theta$)in terms of geometric and hydraulic parameter have been developed.
4. To quantify the momentum transfer occurring at the interface in terms of apparent shear, generalised expressions for estimating the apparent shear force at various interfaces have been derived.The positive value of interaction lengthX_{mc} indicates the transfer of momentum from main channel to flood plain and vice-versa. When magnitude of $X_{mc}$is zero that means it is the suitable interface without momentum transfer and can be chosen as the perfect interface where excludedDCM can be applied.The corresponding DCM can be named as zero shear area method for that geometry and flow conditions.
5. If the apparent shear stress in an assumed interface is equal to the boundary shear stress of the main channel then there is a need of addition of total interface lengthto the wetted perimeters of the main channel to compensate the momentum transfer for the assessment of discharge.The capabilities of these expressions are extremely effective in selecting an interface plane to subdivide the compound channels into zones for discharge calculations. The expression for predicting boundary shear distribution can be modified for channels of differential roughness and channels of non-prismatic sections.

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