# INVESTIGATION ON SHEAR LAYER IN COMPOUND CHANNELS

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**ABSTRACT:**
*A compound channel is a special case of rivers high stage, when the flow spreads to the adjacent floodplains. The bed of the floodplain is generally higher and rougher than the bed of the main channel, so that during flood, the river section consists of a relatively deep main channel and one or two shallow floodplains. The interaction between the faster fluid velocities in the main channel and the slower moving flow on the floodplains causes shear stresses at their interface which significantly distort flow and boundary shear stress patterns. As a result of this, large gradient of depth averaged velocities and boundary shear stress are observed in a region adjacent to the main channel and flood plain interface, commonly known as shear layer region. Identification of this zone for straight compound channels under various hydraulic conditions is integral to research work presented in this paper. Smooth straight compound channel experimental data from FCF series(A) and the depth averaged velocity data from experiment conducted in the laboratory of NIT, Rourkela are analyzed and shear layer width under various geometric and hydraulic conditions are found out. The findings of the analysis are presented and discussed in the paper. Finally mathematical model is presented for computation of shear layer width in a compound channel.*

**KEY WORDS**: Compound channel, Interaction zone, Macro vortices, Shear layer width.

## INTRODUCTION:

Flow in river sections remains confined to the zone between banks on either side called main channel section during most of the year or during normal flow periods. However, during floods very high discharge pass through the rivers and the available cross section of main channel may not permit passage of high magnitude of flow thereby causing the banks to be overtopped and allowing a part of flow to be spilt onto the regions beyond those lying on outer side of banks known as flood plains. These flood plains are generally at a higher level than the invert of the main channel section and are usually covered with vegetal growth and hence are rougher than main channel surface. Flows of these streams are predominantly horizontal since their horizontal dimensions greatly exceed the vertical dimension (Jirka & Uijttewaal, 2004). Although in bounded shear flows the three-dimensional turbulent eddy size is typically, limited to the shortest dimension (the water depth), large-scale, two -dimensional coherent structures with length scales greater than the water depth are observed in a wide range of shallow shear flows (Socolofkssy & Jirka, 2004). There is a significant difference between main channel velocity and flood plain velocity. This is due to sharp decrease in hydraulic radius when the flow goes overbank coupled with increased roughness. Thus shearing occurs at the interface between the main channel and the floodplains (called transition region) which may lead to various flow patterns characterized by large-scale vortical structures with vertical axes ( macro vortices) and other micro vortices of different length and time scales having their axes oriented in all three flow directions. However the former are mainly liable for the transfer of momentum and mass from the main channel to the floodplains when flow goes over bank and the latter are mainly responsible for dissipation of kinetic energy of flow through viscosity in a region lying in the proximity to bed and wall of flow section. As a result, the velocity decreases in the main channel and increases in the floodplains, resulting in a conveyance reduction. For river engineering analysis the prediction of satisfactory Stage-discharge relationship is very fundamental task which needs a thorough understanding of all flow mechanisms associated with the case. There are a number of mechanisms present in natural compound sections .The velocity gradient in the transition region of such flow may produce strong shear layers or mixing layers which leads to generation of plan form macro vortices influenced by inflectional point instability (Sellin, 1964; Ikeda et a1, 1994 & 2001; Ikeda, 1999, Bousmar, 2002). There is also intermittent upward motion of flow at the interface originating due to imbalance of normal Reynolds stresses due to complex nature of channel cross sections. Due to this nature of turbulence secondary flow of Prandtl's second kind occurs giving rise to series of helicoidal vortices rotating in the stream wise direction. The stream wise vortices are generally due to turbulent flows in straight conduits with non circular cross section (Nezu &Nakagawa, 1993). A typical compound cross section showing the possible flow structures for straight geometry is shown in Fig: 1.

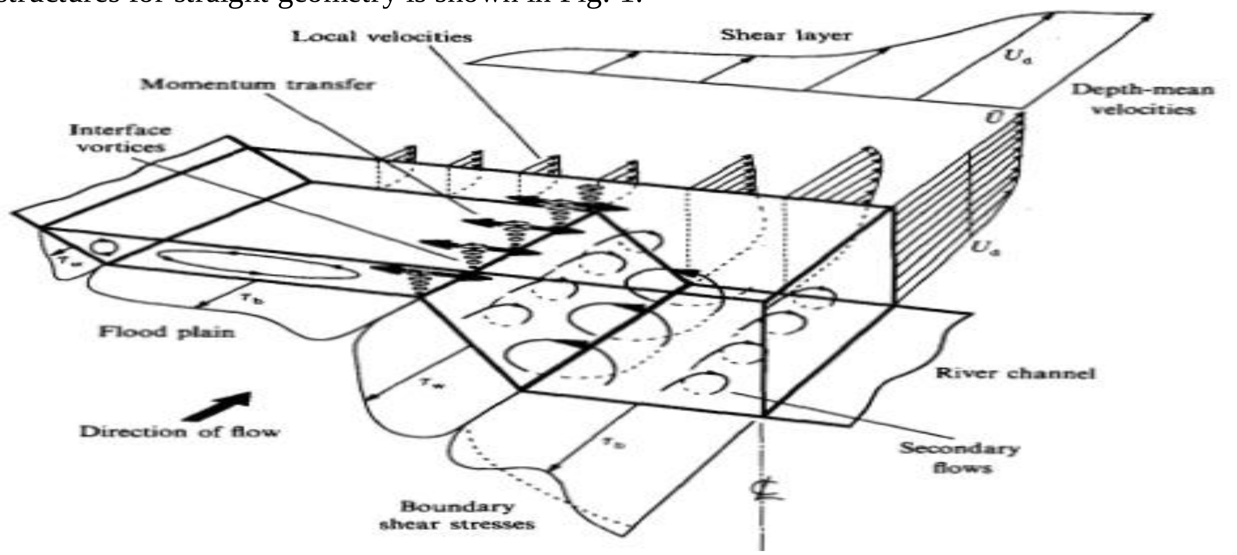
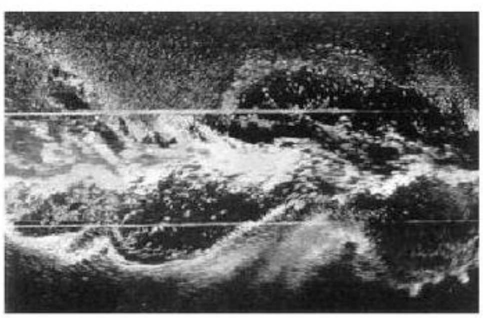


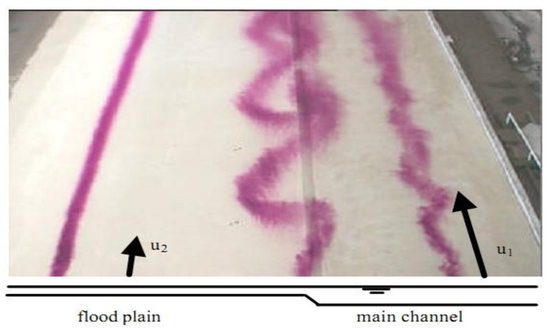

Figure 1 Flow structures in straight compound section (Shiono & Knight, 1991)

Additional complex mechanisms occur for meandering compound channels where in addition to flow structures as present for straight compound cross sections, secondary flow of Prandtl's 1st kind due to imbalance in centrifugal forces between the free surface flow and bottom layer flow inside boundary layer takes place making the flow modeling an onerous task. Many researchers have contributed in the area of compound channel flow modeling and many satisfactory models for stage discharge relationship have been evolved both for straight and meandering plan forms. Significant research contributions are due to the works of Knight & Demetriou (1983); Lambert & Myers (1998); Wormleaton et al, (1982 & 1985); Ackers (1991,1992 a & b, 1993 a& b); Shiono & Knight (1988,1990); Atabay & Knight (2005); Bousmar & Zech (1999); Ervine & Ellis (1987); Shiono et al (1999); Ervine et al (2000); Patra & Kar (2000); Huttoff et al (2007); Khatua (2008) & Khatua et al (2011) etc. A detailed flow analysis by 2D modeling (SKM method, Shiono & Knight,1990 &1991; LDM method, Wark et al,1990, Ervine et al,2000 etc.) or 3D numerical analysis for straight compound channel has revealed the lateral profile of depth averaged stream wise velocity or boundary shear stress where a sharp gradient in the profile is observed near the transition region of compound channel. A strong shear layer or mixing layer is present near the interface where an inflection point (change in sign of velocity gradient) is observed in the indicator variable (depth averaged velocity or boundary shear stress) gradient where intense mixing between fast main channel flow and slow flood plain flow occurs. (van Prooijen et al,2005,; Stocchino & Brocchini,2011, Rhodes&Knight,1995 etc.). The main agents of transport of momentum and mass between the main channel and floodplains are found to be quasi-two dimensional (2D) macro vortices (with vertical axes) generated at the transition region, where there is an intense generation of vorticity owing to the flow jump (Soldini et al.,2004).These macro vortices are of constant size in stream wise direction after their full growth (Stocchino& Brocchini,2010). The role of these macro vortices are extremely important from environmental point of view as the former play a vital role in exchange of mass (e.g. pollutants and nutrients) between the main channel and the floodplains. From river engineering perspective the macro vortices are also important as due to their role in momentum exchange also in addition to mass exchange (Bousmar et al 1999; Bousmar, 2002). Since practically these macro vortices are confined in the regions of shear layer ,so determination of nature and extent of shear layer region (or shear layer width as commonly known) for a compound channel has attracted much interest in last few years. Early research into this subject has been those of Sellin (1964); Zheleznyakov (1965); Rhodes & Knight (1994); Chu & Babarutsi (1988); Rhodes & Knight (1995); Stocchino & Brocchini (2010). The present work aims at furthering the study of shear layer occurrence and quantification and its nature, based on large scale flume data of FCF channels along with the experimental observations from NIT, Rourkela, India.

THEORY OF SHEAR LAYER

The complex mechanism in straight compound channels have been studied previously. Sellin (1964) was perhaps first to notice such mechanisms (horizontal coherent structure) in both laboratory and field compound channels.Fig:2(a) shows the experimental evidence of occurrence of vortices in the transition region of main channel and floodplains. Fig. 2(b) also shows similar eviedence of large coherent structure in a mixing layer experiment of compound channel by van Prooijen et al (2000).


(a)



(b)

Figure 2(a &b)-a: Macro vortices in transition region (Sellin, 1964), b: large coherent structures in mixing layer made visible by dye injection (van Prooijen et al, 2000)

The shear layer in a compound channel has been usually analyzed as a plane mixing layer in a shallow flow (i.e. 2D nature of flow where two horizontal orthogonal dimensions of flow are much large in comparison with the third dimension of flow or depth of flow) and most popular models in determination of stage discharge relationship for compound channel flows are quasi 2D models or depth integrated models (SKM model, Shiono & Knight,1990 & 1991;LDM model, Wark et al, 1990; Model of Ervine et al, 2000; EDM model of Bousmar & Zech, 2002). Although shear is present in between two parallel flowing layers of flow in vertical stream wise direction, from research point of view focus is on large gradient of velocities between sections of fluid in the transition region. This layer extends both towards floodplain zone and main channel zone. The extent of this layer somewhat also scales with size of macro vortices and accurate quantification of its magnitude under a variety of geometry (aspect ratio, Δ where Δ= ratio of bottom width of main channel and height of main channel and width ratio, $\alpha$ where $\alpha$ = ratio of total width of compound channel to the width of main channel= 2B/2b) and flow conditions e.g. relative depth ($\beta$ = H-h/H; where H is total overbank depth and h is main channel depth) is still being investigated.

The quantification and demarcation of shear layer width in case of a compound channel is quite ambiguous in the sense that no exact definition or formula to evaluate the former is available in literature. However various attempts have been made to identify the shear layer zone. Rhodes & Knight (1995) suggested that 'shear layer width' as the extent of the influence of lateral shear, both in the main channel and on the floodplain, can be conveniently quantified by the length scale of intrusion of the shear-layer effects measured as a distance from the main channel-flood plain interface. The concept of a shear-layer width depends on the notion that sufficiently far from the interface and the influence of side walls, a particular flow variable (e.g. depth-averaged primary velocity, bed shear stress or laterally acting depth-averaged Reynolds shear stress) will reach a value that is laterally invariant. The shear-layer width can then be defined as the distance from the interface to a point where there is a 'p' % defect from the laterally invariant value where 'p' value can be assumed as equal to 5 for river engineering purpose (Rhodes& Knight1995). Rhodes & Knight (1995) suggested expressions for estimation of shear layer width in main channel and floodplain regions separately. Also the conclusion from the paper and a previous work by same authors is that the shear layer width has different magnitudes based on different indicator variables chosen for the purpose (Rhodes & Knight, 1994 and Rhodes & Knight, 1995).

Other approaches are based on assumption of plain mixing layer along with some modifications to take into account the effect of uneven bottom in case of compound channel and the finite width of the flow section (van Prooijen et al, 2005).

In Fig.3, a sketch of half cross section of a symmetrical compound channel is shown with trapezoidal main channel having adjacent floodplain. In their attempt to suggest a different model based on momentum exchange in a straight compound channel flow Van Prooijen et al (2005) adopted a new approach for estimating the shear layer width for modeling eddy viscosity.

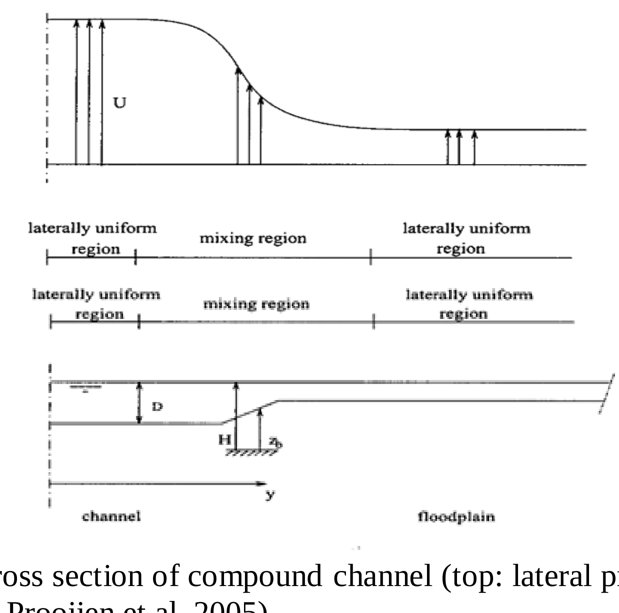



Fig.3. Sketch of half cross section of compound channel (top: lateral profile of velocity, bottom: compound section, van Prooijen et al, 2005)

According to them the contribution of horizontal coherent structures to the total momentum exchange can be modeled by means of Prandtl's mixing length model where the mixing length is adopted proportional to width of mixing layer. In Fig. 4, van Prooijen et al (2005) defined width of such mixing layer (shear layer) 'δ' as twice the distance between the position $y_{25\%}$, where $\bar{U}(y_{25\%}) = \bar{U}f + 0.25(\bar{U}c - \bar{U}f)$ and $y_{75\%}$, where $\bar{U}\ (y_{75\%}) = \bar{U}f + 0.75(\bar{U}c - \bar{U}f)$. So 'δ' is determined as

$$\boldsymbol{\delta = 2(y_{75\%} - y_{25\%})} \qquad \mathbf{(1)}$$

where $\bar{U}c$ and $\bar{U}f$ are defined as depth averaged mean velocities in the main channel and floodplain far from mixing region, respectively.

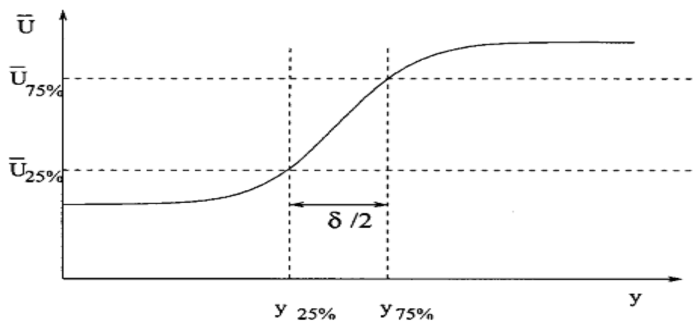



Fig.4. Definition sketch for determination of width of mixing layer (van Prooijen et al, 2005)

## PRESENT ANALYSIS

Based on the latter approach, i.e method of Van Prooijen et a (2005), only smooth straight compound channel experimental results of depth averaged streamwise velocities of large scale FCF channels (Series'A':01,02,03,08and10) are analysed for corresponding geometry and flow conditions, in the first part of the present work . These flow conditions are for different α (width ratio) and β (relative depth) values. The summary of channels' geometry and hydraulic conditions are as given in table.1

For details of FCF experimental channels and test conditions the reader is referred to Knight & Sellin (1987). For these mentioned test cases the depth averaged velocity distribution over lateral positions of compound channel cross section is studied for each β (relative depth) value in each case and adopting the methodology as described by van Prooijen et al (2005), the shear layer width is determined. Particular care was taken to determine $\bar{U}c$ and $\bar{U}f$ as invariant value of main channel and floodplain depth averaged velocities from available FCF data. It though remained a subjective decision as nowhere in the distribution a true invariant value is observed in reported data (www.flowdata.bham.ac.uk). However from practical point an estimated value was adopted by taking average of some data points which showed minor variation in far field region away from interface and away from wall.

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

| Test channel | Series No. | Longitudinal slope ($S$) | Main channel Width ($2b$) in mm | Main channel depth ($h$) in mm | Main channel side slope(s) | Total width ($2B$) in mm | Observed discharge ($Q$) range in m3/s | Width ratio ($\alpha$) | Range of Relative depth ($\beta$) |
|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| FCF Series-A channels | 01 | 1.027×10 -3 | 1500 | 150 | 1.0 | 10000 | 0.2082-1.0145 | 6.67 | 0.056-0.400 |
| | 02 | 1.027×10 -3 | 1500 | 150 | 1.0 | 6300 | 0.212300-1.114200 | 4.2 | 0.0414-0.479 |
| | 03 | 1.027×10 -3 | 1500 | 150 | 1.0 | 3300 | 0.2251-0.8349 | 2.2 | 0.0506-0.500 |
| | 08 | 1.027×10 -3 | 1500 | 150 | 0 | 6000 | 0.1858-1.1034 | 4 | 0.0504-0.499 |
| | 10 | 1.027×10 -3 | 1500 | 150 | 2.0 | 6600 | 0.2368-1.0939 | 4.4 | 0.0508-0.464 |
| Channel at NIT Rourkela | 01 | 0.0019 | 120 | 120 | 0 | 440 | 0.008726-0.039071 | 3.67 | 0.118-0.461 |

Fig.5.The experimental flume with fabricated compound channel and other accessories at NIT, RKL. (Left: side looking photo; Right: looking upstream)

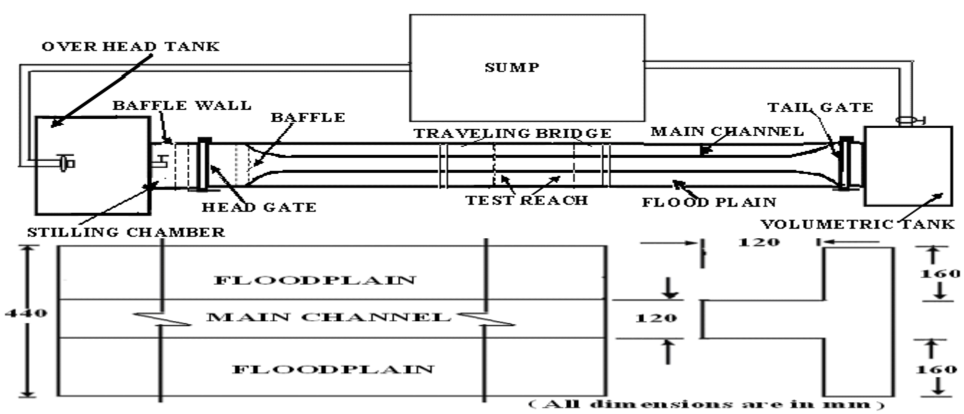
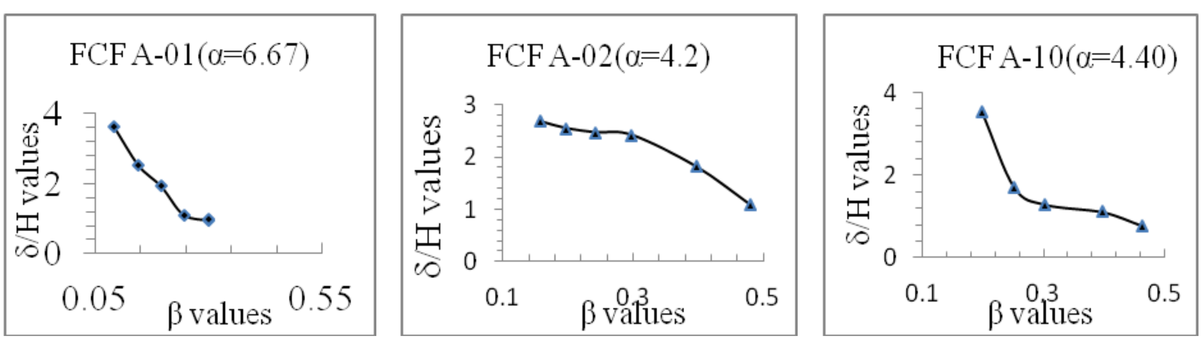



Fig.6.Experimental arrangements of the Compound channel (top); plan view of compound channel (bottom)

In the second part of the work experiments were conducted in fluid mechanics and Hydraulics laboratory of NIT, Rourkela, India, in a symmetric straight compound channel of rectangular main channel section flanked by two adjacent floodplains on either side. Such a channel was built inside a tilting steel flume and the wall and bed were made up of perspex sheets (6mm thick) having manning's roughness value as 0.01. Experimental arrangements of the compound channel and its plan view are shown in Fig.5 and Fig.6 respectively. Water was supplied to the flume from an underground sump via an overhead tank by centrifugal pump (15 hp) and recirculated to the sump after flowing through the compound channel and a downstream volumetric tank. In the upstream section in the flume flow straightener and baffle walls were provided to subdue the effects of turbulence and for stilling the water. A tailgate is provided in the downstream section to achieve near uniform flow conditions. By varying the discharge in the compound channel, various sets of hydraulic conditions ($\beta$ values) could be achieved. At the predetermined grid positions on the entire cross-sectional domain of the compound section point velocities were measured by Pitot tube (6.00 mm Ø) at different points on verticals positioned laterally throughout the main channel and floodplain section. At each vertical a suitable curve was best fitted to the point velocity values and from depth integrating the expression of best fit velocity distribution the depth averaged velocity was obtained. Likewise the procedure was adopted for all lateral positions of the verticals taken over the cross section. In this way for each relative depth ($\beta$) value the depth averaged velocity distribution could be obtained and taken for analysis in the present work. The methodology was repeated for FCF data for calculating all the parameters necessary for computation of shear layer width. The results along with discussion are presented in next section.

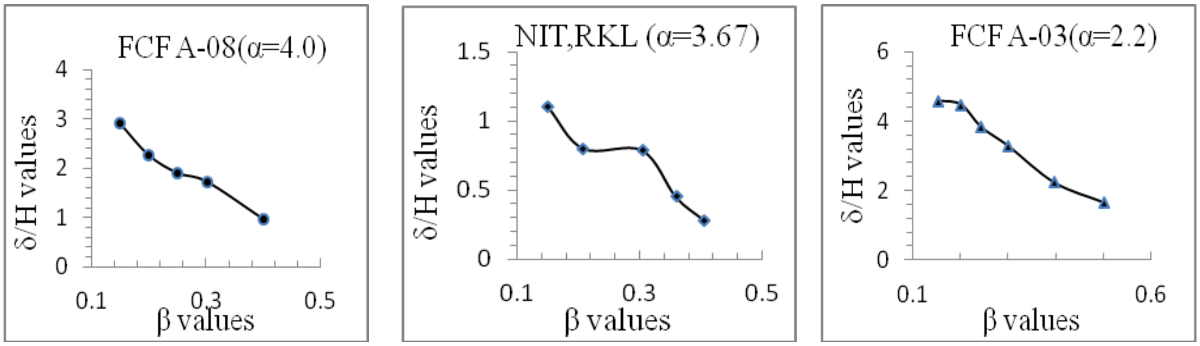
## RESULTS AND DISCUSSION

The computed shear layer width ($\delta$) is non-dimensionalised with depth of flow in the main channel (H) and its variation with relative depth ($\beta$) is presented for all the FCF series data as well as for NIT, RKL, and channel in Fig.7 (a-f). although the geometry of main channel is not similar (Series 1-3 &10 of FCF are trapezoidal; others are rectangular) and the width ratios ($\alpha$) is different (Table.1), still some interesting features are evident from the Fig.7. As detailed velocity distribution data could not be available for some low relative depth ( $\beta$ ) values ,the plotting was done taking into account variation of shear layer width starting with moderate $\beta$ ( >0.10) values although it did not affect the study much as trend of shear layer growth was apparent. It is seen almost everywhere the $\delta$/H values decrease with increasing relative depth. Of course the rate of such variation is different for different series.




(a) (b) (c)

Fig.7: For caption see facing page.




(d) (e) (f)

Fig.7(a-f):Variation of shear layer width(δ) non dimensionalised by depth of flow(H) with relative depth(β) for different channels.

It is ascertained that shear influence in compound channel is very much dependent upon relative depth. Further on analysis of two rectangular channels (FCF series 8 and NIT, RKL;both having nearly same α values)as shown in Fig.7 (d & e), distinctly different shear layer width variation is observed which implies that the extent of shear layer is also aspect ratio dependent.

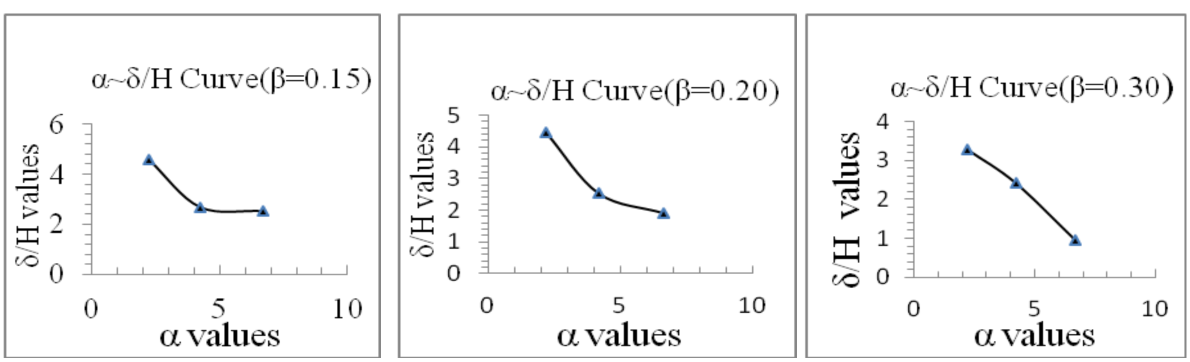
From Fig. 7 it is clear that the shear layer width decreases rapidly with increasing width ratios. In very wide floodplains the influence of main channel & floodplain interaction is limited to a zone near the interface region and the flow remains unaffected in major portion of the floodplain. These findings are very important from sedimentation studies point of view for the floodplain region. Finally a multiple regression analysis was done among the data series (FCF A-01, 02& 03) of only varying α values and it was found that shear layer width is strongly correlated with β and relatively weakly with α. Coefficient of determination $R^2$ value was found as equal to 0.9. The mathematical model may be presented as

$$\frac{\delta}{H} = 6.76094 - 8.13643\beta - 0.48609\alpha \qquad (2)$$

Similar regression analysis was done replacing β with$\left((\bar{U}c - \bar{U}f)|\bar{U}c\right)$ i.e. in terms of invariant velocity in main channel ,$\bar{U}_c$ and in floodplain, $\bar{U}_f$ the model can be presented as

$$\frac{\delta}{H} = 1.6084 + 4.6374((\bar{U}c - \bar{U}f)|\bar{U}c) - 0.34248\alpha \qquad (3)$$

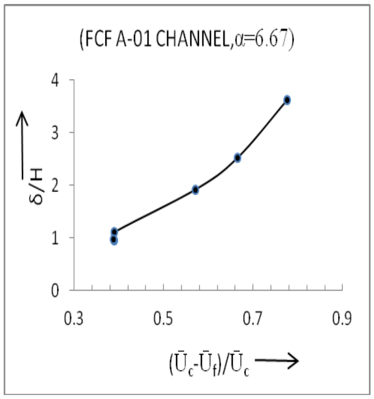
$R^2$ value for equation(3) was estimated as equal to 0.93, which signified a better correlation than equation (2).In other words shear layer width was found to be more dependent on difference in velocities in main channel and floodplain than relative depth.



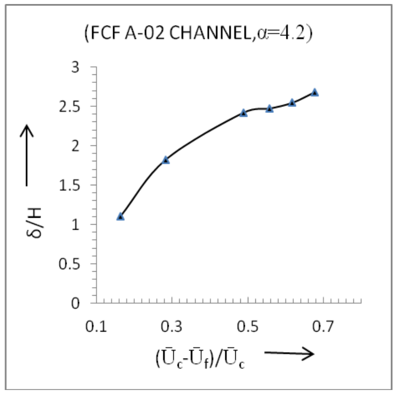

(a) (b) (c)

Fig.8(a-c); Variation of shear layer width(δ) non dimensionalised by depth of flow(H) with width ratio(α) for different channels.

In Fig.8 (a-c) for same relative depth values, the variation of shear layer width is shown among FCF channels of series (A) 1, 2 & 3 having same aspect ratio but of varying width ratio (6.67, 4.2 & 2.2 respectively) values. Also relationship between shear layer width (δ) and $\left((\bar{U}c-\bar{U}f)\middle|\bar{U}c\right)$ i.e .difference between invariant velocity in main channel ,$\bar{U}_c$ and in floodplain, $\bar{U}_f$ are shown through a series of graphs {pl. see Fig.9(a-f)|\}. The trends in these Figures justify the good value of $R^2$ obtained for equation(3).




(a)

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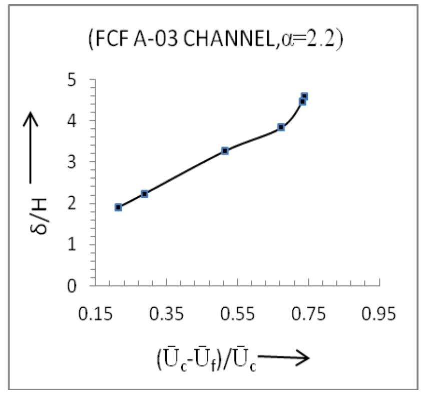
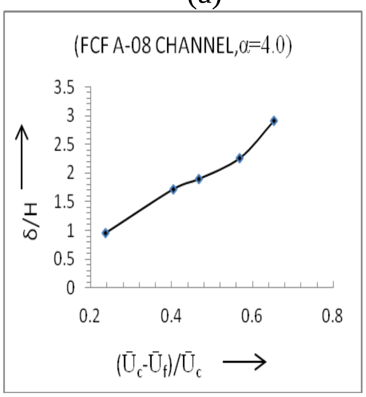
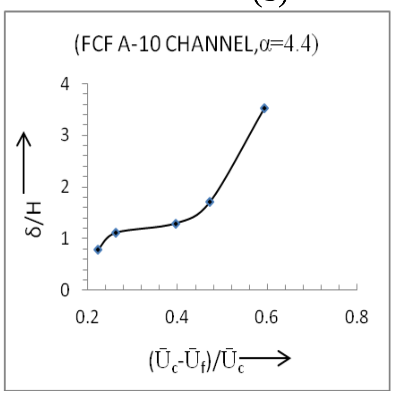


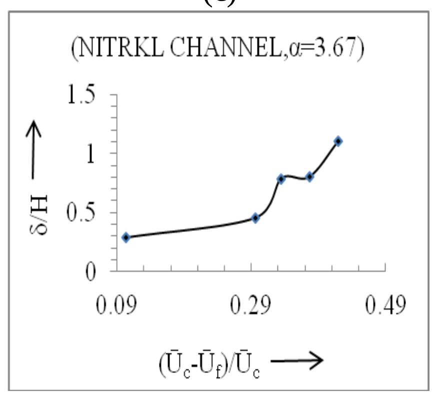

(c)




(d)




(e)




(f)

Fig.9(a-f); Variation of shear layer width(δ) and $(\bar{U}_c - \bar{U}_f)/\bar{U}_c$ ( i.e.difference between invariant velocity in main channel ,$\bar{U}_c$ and in floodplain, $\bar{U}_f$ normalized by $\bar{U}_c$ ) for different channels.

## CONCLUSIONS

Depth averaged velocity distribution from different experimental channels of FCF Series (A) are used in this study to compute shear layer width under different geometric and hydraulic conditions. Also experiments were conducted in fluid mechanics and hydraulics laboratory of NIT,Rourkela in a straight smooth rectangular compound channel and velocity data were used for analysis and comparison purpose. In view of very limited research in the area of determination and computation of zone of shear influence in a compound channel, this analysis has special importance in the river engineering as prediction of accurate shear zone has a bearing on floodplain sedimentation studies. The main findings of this analysis can be summed as under:

(a) Shear layer width is rather a subjective decision in view of absence of a pure shear free region in compound channels of finite width as encountered in laboratory environment.

(b)Nevertheless, using the approach adopted by previous researchers the width of shear layer could be computed both for large scale channel data of FCF series (A) and experimental observations. All cases considered were of smooth straight compound channels having different geometry e.g. aspect ratio and width ratio.
(c)Shear layer is both geometry dependent and flow dependent. With increasing width ratio shear layer growth decrease and vice versa. Similarly with increasing relative depth the growth of shear layer decreases and increases with decreased relative depth.
(d) Shear layer growth is also dependent on side slope of main channel, although exact nature of such variation could not be ascertained for want of limited experimental data series.
(e)New mathematical models are presented relating shear layer width with relative depth, width ratio and difference between invariant values of velocity in main channel and floodplain.

## SCOPE FOR FUTURE WORK

The determination of shear layer width in a compound channel is an interesting and difficult task. It has so far been dealt with very sparsely as found from survey of literature, may be due to inherent subjectivity and inadequate availability of data from laboratory and/or field case studies. The present work can also be extended to include the effects of roughness and sinuosity of the main channel and flood plains under varying conditions to simulate the flow variations encountered in situ. Also exact methodologies along with accurate mathematical expressions may be devised so as to further research in this area for its applicability in river engineering.

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