APPLICATION OF SHIONO AND KNIGHT METHOD IN ASYMMETRIC COMPOUND CHANNEL FLOW

K. Devi[1] K. K. Khatua[2] J. R. Khuntia[3]

[1&3]*Research Scholar,Civil Engineering Department, National Institute of Technology,Rourkela,769008,India*

[2]*Associate Professor,Civil Engineering Department,National Institute of Technology,Rourkela,769008,India*

[1]*Email: kamalinidevi1@gmail.com ,[2]Email: kkkhatua@yahoo.com ,[3]Email: jnanaranjan444@gmail.com*

ABSTRACT

During flood, the river overflows either side of its flood plain is known as asymmetric compound channel otherwise it is called as symmetric one where, it inundates both side flood plains. Due to the three-dimensional structure of flow, modeling of depth averaged velocity and boundary shear stress in an asymmetric compound channels is an exigent task. The analytical solution to the Shiono and Knight Method (SKM), accounts three governing parameters i.e., bed friction, lateral shear and secondary flows for this complex flow phenomenon. In order to investigate the influence of these coefficients on flow parameters in an asymmetric compound channel, experiments were employed in smooth beds. Measurements were made to find distributions of boundary shear stresses and depth averaged velocity. Some experimental data sets from large flood channel facility and from investigations made by other researchers have also been used in this study. The variation of three calibrating coefficients i.e., eddy viscosity coefficient (λ), friction factor (f) and secondary flow coefficient (k) with different geometric and hydraulic parameters have been discussed. The usefulness of these coefficients for application in SKM has been suggested. The study will helpful for accurate determination of boundary shear and depth averaged velocity distribution in asymmetric compound channels.

Keywords: *Shiono and Knight Method, secondary flow, eddy viscosity, depth averaged velocity, boundary shear*

1. INTRODUCTION

Rivers are most essential to our lives in various ways and are the main supplies of our basic needs. Firstly it is used as our drinking water; secondly, it nourishes our crops which are another basic need of human and provide substantial transportation benefits. However, the disadvantages of river occur when the flow of water overtops its bank and inundates the adjoining flood plains during heavy precipitation which often leads to flooding and forming compound sections. In order to make efficient use of rivers and channels, measurements of different properties of rivers e.g., depth and flow are required to obtain. The measurements are usually accomplished by two methods; directly by measurements and indirectly using numerical models. In last few decades, considerable attention has been focused on the development of simple models for predicting the flow parameters like depth averaged velocity, boundary shear distribution and discharge based on the solution of the Saint Venant equations (Sharifi 2009). Among these simple models, Shiono & Knight method (SKM) is a quasi 2D model developed by Shiono & Knight(1991) based on Reynolds Averaged Navier Stokes (RANS) equation, popularly used worldwide by modifying the original one (Ervine *et al.*, 2000 and Bousmar and Zech, 2004). The depth averaged RANS equations adopted in Shiono Knight Method requires three calibrating coefficients i.e., friction factor, dimensionless eddy viscosity and secondary flow coefficients as their input parameters. Devi and Khatua (2016) worked on the calibrating coefficients by considering symmetrical compound channels. So, this current work examines the application of Shiono Knight Method to predict boundary shear and depth averaged velocity distribution in asymmetrical compound channels. In this study, the framework of SKM has been applied to homogenous compound channels having one sided flood plain. The variations of the three coefficients with relative flow depths and width ratio have been investigated. Appropriate empirical equations for deriving these coefficients are presented here in by taking a large series of experimentations.

2. THEORETICAL ANALYSIS

For steady uniform flows, the Reynolds-Average Navier-Stokes equation (RANS) is simplified as

$$v\frac{\partial^2 \bar{u}}{\partial y^2} + v\frac{\partial^2 \bar{u}}{\partial z^2} - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z} + g\left\{\frac{\partial h}{\partial x} - S_0\right\} = \frac{\partial \bar{u}\bar{v}}{\partial y} + \frac{\partial \bar{u}\bar{w}}{\partial z} \qquad (1)$$

This equation is applicable for obtaining the turbulent flow structure in different flow conditions. The RANS equation in X direction (longitudinal flow direction) can be simplified as

$$\rho\left[\frac{\partial \bar{u}\bar{v}}{\partial y} + \frac{\partial \bar{u}\bar{w}}{\partial z}\right] = \rho g S_0 + \frac{\partial}{\partial y}\left(-\rho\overline{u'v'}\right) + \frac{\partial}{\partial z}\left(-\rho\overline{u'w'}\right) \qquad (2)$$

Where ρ the density of the water, S_0 the longitudinal bed slope, g the acceleration due to gravity, $\bar{u}$, $\bar{v}$ and $\bar{w}$ are the component of the mean velocity, u', v' and w' are the fluctuation of the velocity components. Here the over bar represents a time averaged parameters.

Where, $\alpha = \frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{s\sqrt{8f}\sqrt{1+s^2}}{\lambda}}$; $= \frac{gS_0}{\frac{\sqrt{1+s^2}}{s}\left(\frac{f}{8}\right) - \frac{\lambda\sqrt{f/8}}{s^2}}$; $\eta = \frac{-\Gamma}{\rho\left(\frac{f}{8}\right)\sqrt{1+\frac{1}{s^2}}}$; $\xi = H + \frac{y+b}{s}$ (for positive y) $\xi = H - \frac{y-b}{s}$ (for negative y)

The cross section of an asymmetric compound channel can be divided into number of panels, in which the three calibration coefficients f, λ, Γ need to be calibrated for evaluation of U_d in the lateral direction of a compound channel. The panels are either of constant depth domains or of variable depth domains e.g., for the trapezoidal channel in Fig.1, panel 1 and 3 are of constant depth domain and panel 2 and panel 4 are variable depth domains. The accurate prediction of depth averaged velocity and boundary shear stress depends on proper estimation of the calibrating coefficients in all panels.

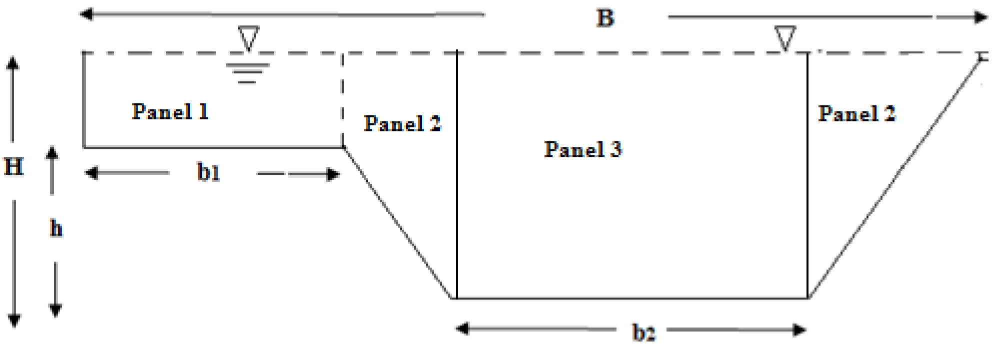

Figure 1. Sub-section of an asymmetric compound channel

For assessing the Darcy-Weisbach friction factor (f), experimental depth-averaged velocity distribution and boundary shear stress data sets are necessary, from which the friction factors can be back-calculated using the equation $\tau = \frac{f}{8}\rho U_d^2$. For finding the dimensionless eddy viscosity coefficients (λ), Knight (1999) suggested the ranges and some specific values obtained from experimentations which are described later part of this paper. Secondary current (Γ) depends upon the average boundary shear stress per panel (say τ_{avg}) and average boundary shear stress of whole compound section i.e., $\rho g H S_0$. A factor k which is the ratio of average boundary shear stress to the total average boundary shear stress $\rho g H S_0$ has been introduced as secondary flow coefficient.

3. EXPERIMENTAL DETAILS

In this present study, three sets of asymmetrical compound channels were constructed using plain cement concrete in the hydraulic engineering laboratory of the Civil Engineering Department, National Institute of Technology, Rourkela, India. The main channel is 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 slope along flow direction is fixed with a value 0.001 for all three cases satisfying subcritical flow conditions. As the channels are considered smooth, the roughness of main channel and flood plain are estimated from the inbank flow as same having Manning's *n* of 0.01. Boundary shear measurements on bed and wall have been done by Preston tube method using Patel's (Patel, 1965) calibration curve. The second series of data chosen for the present analysis are from the large scale compound channel facility i.e., Flood Channel Facility, UK with width ratio(α) of 2.7, located at the laboratories of HR Wallingford Ltd shown in Fig 2. The geometrical parameter such as total width of main channel is 10 m, aspect ratio of main channel is 10, longitudinal slope of the channel is 0.001027 and Manning's roughness coefficient is 0.01. All the experiments in this channel were also done under subcritical flow conditions. Finally the last series of data chosen for the present analysis are from the asymmetrical compound channel data of Atabay(2001). He performed all the experiments in the hydraulics laboratory at Birmingham University, using a flume which was 120 cm, wide, 40 cm deep and 18 m long with a fixed channel bed slope of 0.002024. The plan views with cross sectional details of all experimental channels have been demonstrated in Fig.2.

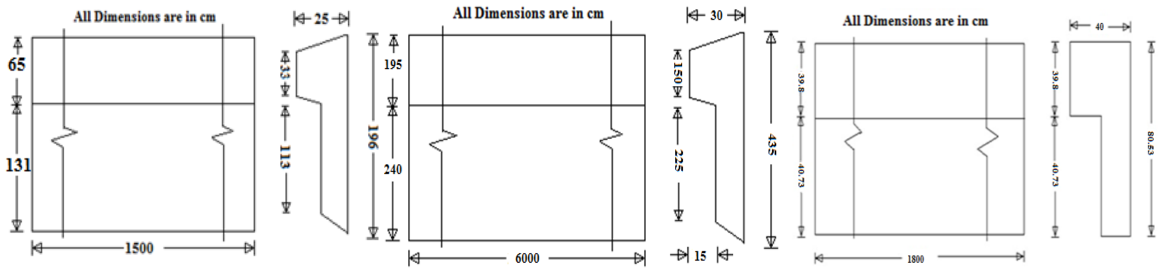

Figure 2. Plan and sectional View of Experimental asymmetrical compound channels of NITR, FCF Series 6 and Atabay (2001)

4. RESULTS AND ANALYSIS

4.1 Determination of calibrating coefficients

Knight (1999) showed from experiments that the values of eddy viscosity (λ) are only in the range of 0.07 to 0.50, with values being 0.067 for boundary layers, 0.13 for open channels, and 0.16 for trapezoidal data, 0.27 for FCF smooth floodplains and 0.22 for FCF rough flood plains. Based on experimental study in the Flood channel facility, he stated that their numerical model is insensitive to the dimensionless eddy viscosity (λ) which can be taken as a constant across the channel.

Considering this point in view, the detail study of dimensionless eddy viscosity (λ) with flow depth and geometry has not been carried out in current analysis. For the present case the dimensionless eddy viscosity (λ) of the main channel has been considered as per Knight(1999) and for the flood plain the value has been evaluated as suggested in Abril and Knight (2004) i.e.,

$$\lambda_{fp} = \lambda_{mc}(-0.2 + 1.2Dr^{-1.44}) \quad (16)$$

Solution of equation (8) requires the proper value of calibrating coefficient *f*, λ and k that govern bed resistance, lateral shear and secondary flow respectively. Main channel region and the flood plain regions resemble particular friction factors f_{mc} and f_{fp} for their zones which can be calculated from

$$f_{mc} = \frac{8n_{mc}^2 g}{R_{mc}^{1/3}} \quad \text{and} \quad f_{fp} = \frac{8n_{fp}^2 g}{R_{fp}^{1/3}} \quad (17)$$

Where f_{mc} and f_{fp}, R_{mc} and R_{fp}, n_{mc} and n_{fp} are the friction factors, hydraulic radius and Manning's roughness coefficients of the corresponding main channel and flood plains, g is the gravitational acceleration; R_{mc} and R_{fp} are the hydraulic radius defined as the ratio of area to the wetted perimeter of the channel.

Then for the secondary flow coefficients as used in equation 15, three different values of *k* have been considered, first one for main channel (Panel 3) i.e., constant depth domain (k_{mc}), second one for side slope panel (Panel 2) i.e., variable depth domain (k_s) and third one for flood plain bed region (Panel 1) i.e., constant depth domain (k_{fp}).

where $k_{mc} = \frac{\tau_{avg}}{\rho g H S_0}$, $k_s = \frac{\tau_{avg}}{\rho g h' S_0}$, and $k_{fp} = \frac{\tau_{avg}}{\rho g (H-h) S_0}$ (18)

where h' is the average flow depth of side slope region (Fig. 1).

The variations of friction factors and secondary flow coefficients in main channel and flood plains against relative flow depths for each experimental channel have been presented.

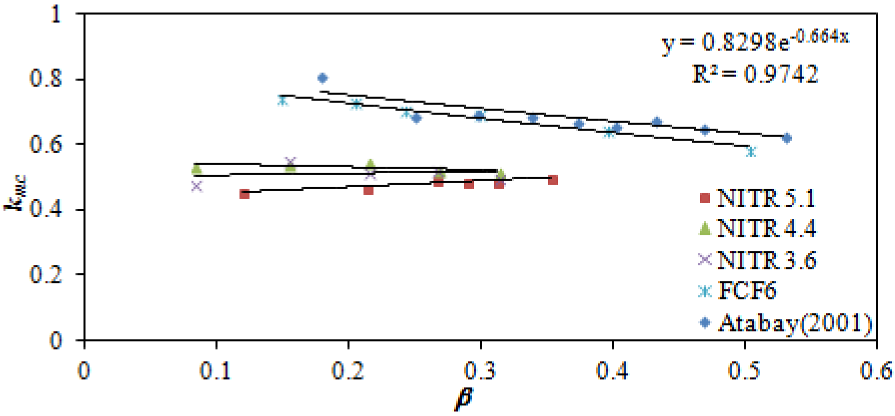

Figure 2(a). Variation of secondary flow coefficient in main channel (k_{mc}) with relative flow depth

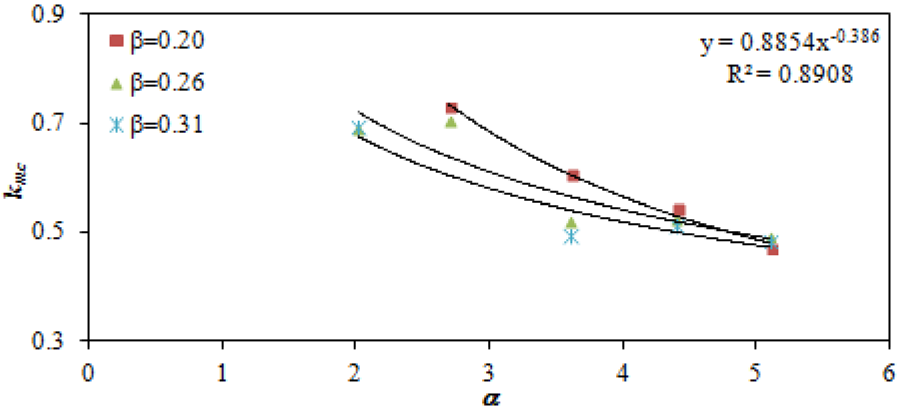

Figure 2(b). Variation of secondary flow coefficient in main channel (k_{mc}) with width ratio

Using the five experimental data sets of asymmetric channels of NITR, FCF series 6 and Atabay (2001), the effect of flow and geometric parameters on the secondary flow coefficients k_{mc}, k_{fp} and k_s have been investigated. Fig.2 (a) and Fig.2 (b) respectively highlight the influence of relative flow depth and width ratio i.e., flood plain width on variation of secondary flow coefficient of main channel k_{mc}. Fig.2 (a) displays the values of k_{mc} are inversely proportional to flood plain width as the greater values of k_{mc} are found when width ratio of channels are decreasing. This Fig.2 (a) also manifests that, there is a falling trend of k_{mc} against relative flow depth for shallow flood plain cases i.e., FCF series 6 and Atabay (2001).

Variation of secondary flow coefficients of flood plain (k_{fp}) with relative flow depth and width ratio have been graphically demonstrated in Fig.3 (a) and (b) respectively. A significant decrease of k_{fp} with relative flow depth has been observed for every width ratio channel in Fig.3 (a) which indicates the effect of flood plain shear stress are decreased with increase of flow depth over flood plain because of the less intensity of momentum transfer at higher flow depth.

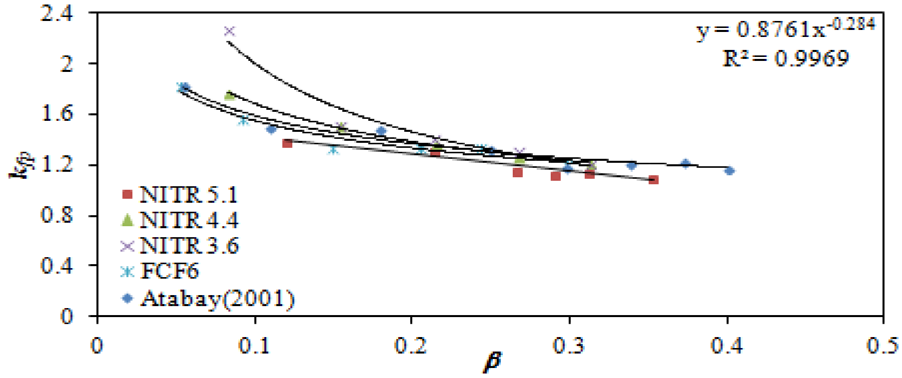

Figure 3(a). Variation of secondary flow coefficient in flood plain (k_{fp}) with relative flow depth

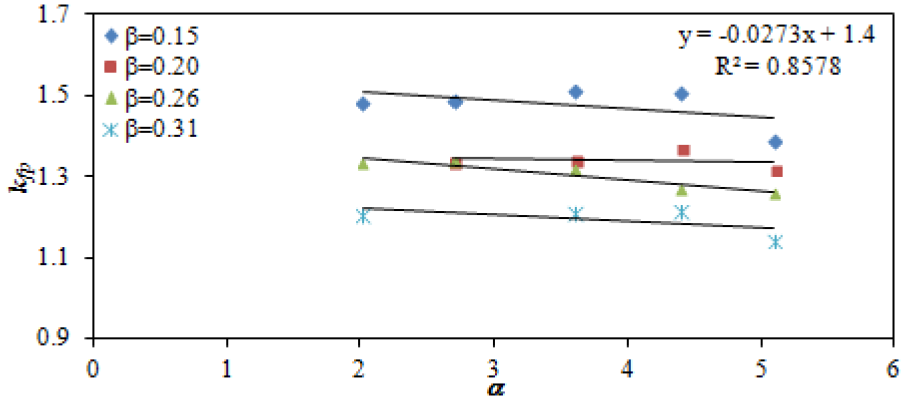

Figure 3(b). Variation of secondary flow coefficient in flood plain (k_{fp}) with width ratio

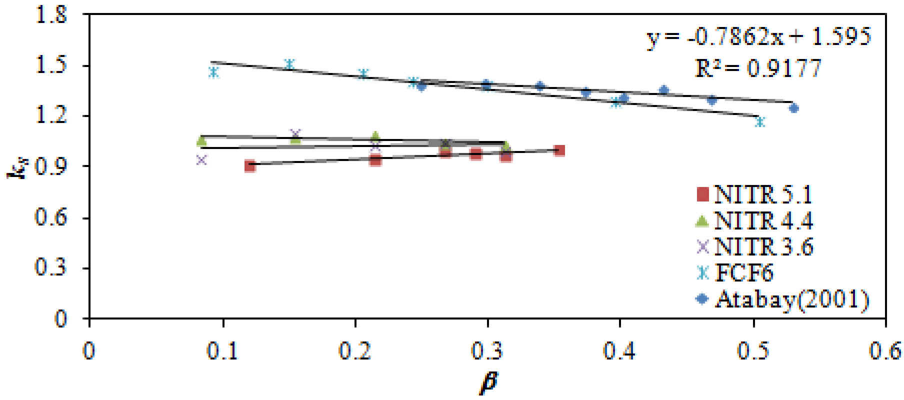

Figure 4(a). Variation of secondary flow coefficient in bank slope region (k_s) with relative flow depth

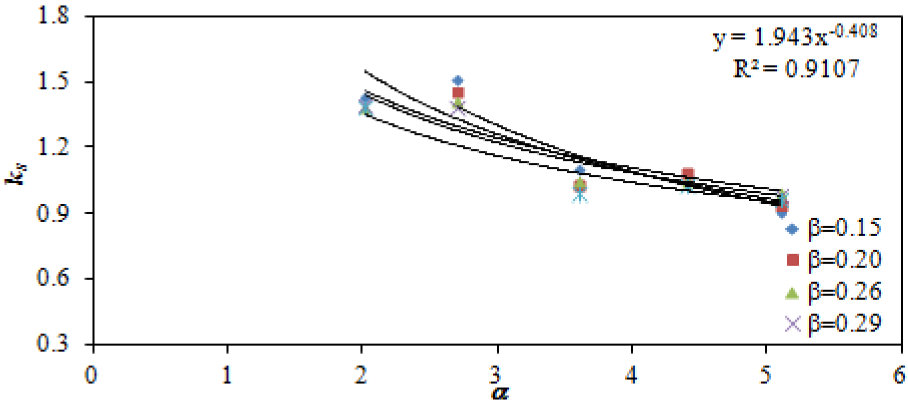

Figure 4(b). Variation of secondary flow coefficient in bank slope region (k_s) with width ratio

Fig.4 (a) and (b) respectively highlight the effect of flow and geometric parameter on variation of the secondary flow coefficient of side bank region (k_s). Identical results have been perceived here for k_s as like as in case of k_{mc}. Again the value of k_s is reducing with higher relative flow depth for low width ratio channel and is increasing with high width ratio channel (Fig.4 a). With increase of width ratio, the k_s value decreases indicating less intensity of momentum exchange at junction. Hence from Fig.2, Fig.3 and Fig.4, it can be concluded that the secondary flow coefficients are flow and geometry depended.

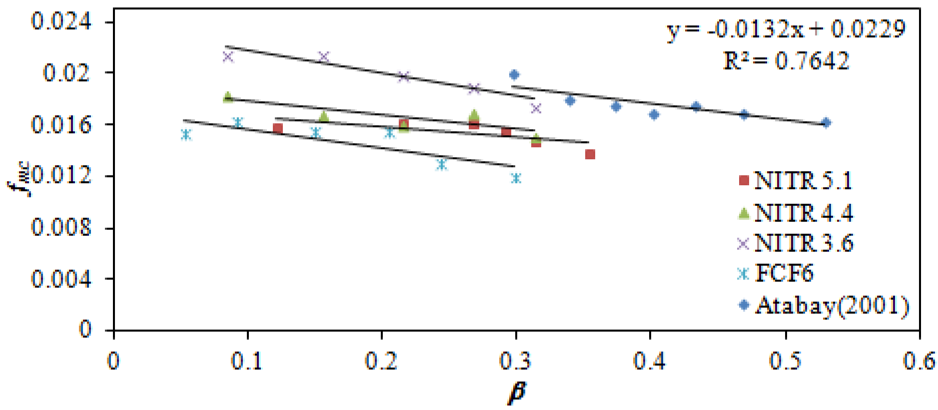

Figure 5(a). Variation of friction factor in main channel (f_{mc}) with relative flow depth

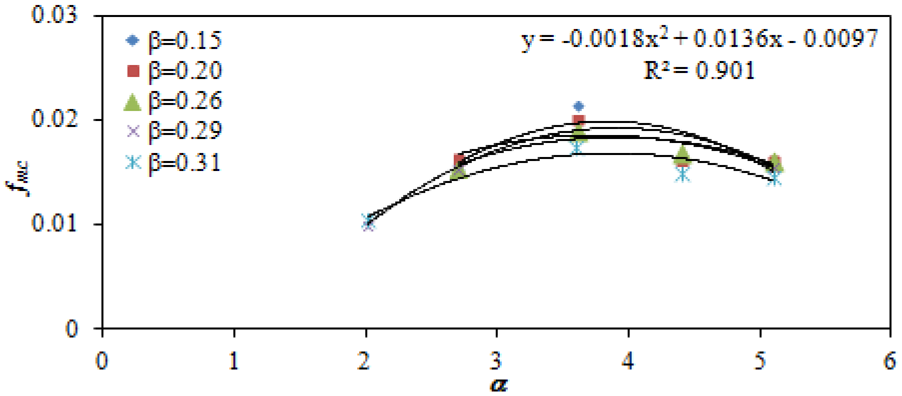

Figure 5(b). Variation of friction factor in main channel (f_{mc}) with width ratio

Fig.5 (a) and Fig.5 (b) show the variation of friction factor in the main channel and flood plain with relative flow depth (β) and width ratio (α) respectively. There is a significant decrease of friction factor in main channel with increase of β as demonstrated in Fig.5 (a). Fig.5 (b) illustrates the variation of friction factor against the width ratio keeping constant relative flow depth. The trend is polynomial in nature that indicates an increase of friction factor in main channel with increase of width ratio for a certain limit. Further increase of width ratio, the trend falls for all relative flow depth cases.

Fig.6 (a) and (b) illustrates the corresponding variation of friction factor over flood plain with flow parameter i.e., relative flow depth and geometric parameter with width ratio. The falling trend of f_{fp} with relative flow depth is logarithmic in nature and the variation of f_{fp} against width ratio is polynomial in nature.

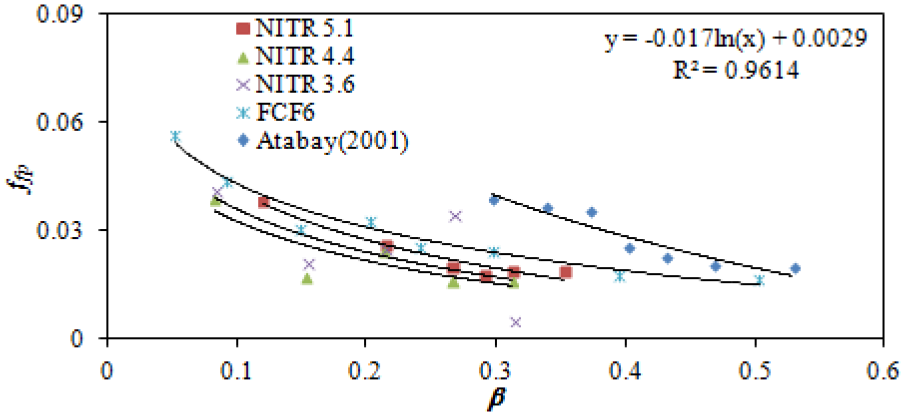

Figure 6(a). Variation of friction factor in flood plain (f_{fp}) with relative flow depth

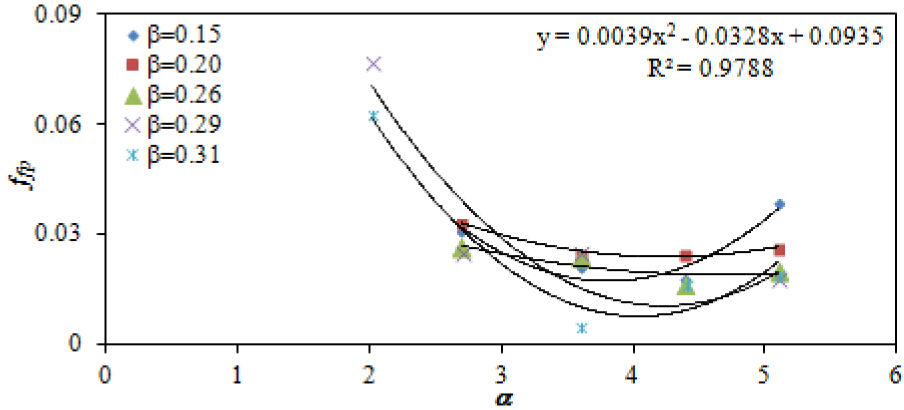

Figure 6(b). Variation of friction factor in flood plain (f_{fp}) with width ratio

The analytical depth-averaged velocity and boundary shear stress distributions by Shiono Knight Method require proper values of the calibrating coefficients for the accurate prediction. Based on the present discussion on variation of these coefficients against different flow and geometric conditions, analytical modeling may further carried out for precise prediction of these input parameters before applying SKM.

CONCLUSION

Experiments have been investigated in three asymmetric compound channels of different width ratio for examining and studying the variations of different flow parameters. The popular Shiono Knight Method for predicting the depth averaged velocity and boundary shear stress distribution has been briefly discussed. The variation of the calibrating coefficients required in SKM have been presented and discussed by taking own experimental data sets along with the data sets of FCF and other investigators. A significant decrease in values of secondary flow coefficients k_{mc}, k_{fp} and k_s with relative flow depth have been observed for every width ratio channel which indicates the effect of main channel shear and flood plain shear stress decrease with increase of flow depth over flood plain. Based on the present discussion on variation of these coefficients against different flow and geometric conditions, analytical modeling may further carried out for precise prediction of the input parameters before applying SKM. Good agreement between experimental and SKM can be possible in main channel and flood plain region by following these modeling of coefficients.

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