Analysis of Depth Averaged Velocity in Meandering Compound Channels

Prof. K.C.Patra, Ellora Padhi, Laxmipriya Mohanty & Manaswinee Patnaik.

Department of Water Resources Engineering,
National Institute of Technology, Rourkela, India

ABSTRACT: Analysis of flow in a compound channel is strongly influenced by the complex geometry associated with uncertainties on every measurable property such as the width ratio, aspect ratio, relative depth and the channel sinuosity. For the present work, experimentations have been conducted in three different rigid smooth compound channels with sine generated rectangular compound channel flanked by floodplains on one or both sides. The meandering compound channels are having three different width ratio, aspect ratio. Sinuosity of the main channel are 1.225, 1.210, 1.043 respectively. An analysis has been done to present the lateral distribution of cross sectional depth averaged velocity, which in turn is used to quantify the momentum transfer at the interface of the main channel and the flood plain and to predict the flow distribution at different sub sections of the compound meandering channel. Modifications to the approaches are proposed. The study serves for a better understanding the flow and velocity patterns in a meandering compound channel.

1. INTRODUCTION

Meandering represents a degree of adjustment of water and sediment laden river with its size, shape, and slope such that a flatter channel can exist in a steeper valley. During floods, rivers have compound sections consisting of a main channel, which always carry low flows and one or more side floodplains, which carry flow above the bank full stages. The cross sectional geometry of flow undergoes a sudden change when the flow depth changes from in bank to overbank, a situation common to most of the natural or man-made channels. There is existence of a large shear layers generated by the difference of velocity between the main channel and the floodplain flow. There is also a wide variation in the distribution of longitudinal velocity from the inner to the outer bank of a meandering compound channel section. The flow geometry in a meandering channel is in the state of either development or decay or both. Distribution of flow and velocity in a meandering river are important topics in river hydraulics to be investigated from a practical point of view in relation to the bank protection, navigation, water intakes, and sediment transport-depositional patterns. Knowledge on velocity distribution in a channel also helps to determine the energy expenditure, bed shear stress distribution, and the associated heat and mass transport problems.

An attempt is made here for an analytical solution of longitudinal depth averaged velocity distribution in meandering compound channel at any section in the meandering path. More efforts are made to model the distribution of flow between the main channel and floodplain of a meandering compound channel.

The usual practice in one-dimensional (1D) analysis of compound channel is to calculate separately the flow that can be conveyed by the various discrete subareas of a compound section as if the subareas are independent. Manning equation is used to calculate the conveyance capacity using appropriate values for the area, wetted perimeter, and roughness coefficients of the subareas, the individual discharges are then added to give the total discharge carried by the compound section. The roughness coefficient *n* is a somewhat crude measure of the net effect of the influences of the shear and the secondary flow, wherein all the hydraulic effects are lumped into a simple bulk resistance parameter. Using ‘‘divided channel’’ method (Lotter, 1933) and following others work (Wormleaton et al., 1982, Knight and Demetriou, 1983 and Knight and Hamed, 1984, Patra and Kar, 2000, 2004) the present work is proposed to calculate the depth averaged velocity across the cross section of meandering compound channels. The percentages of total flow carried by the main channel and floodplain of a compound section in terms of four dimensionless channel parameters were suitably modeled.

The effect of flow interaction between the floodplain and main channel for various depths of flow over floodplain was adequately taken care of. Two-dimensional (2D) turbulence models (Keller and Rodi 1988; Shiono and Knight, 1990; Wark et al., 1990; Shiono 1993; Abril and Knight, 2004; Abril 1995; Knight and Stokes, 1996) of compound open channel flows were developed to give the depth averaged flow characteristics. Clearly a 2D model is superior to the 1D model as more use may be made of the lateral output than the bulk values. The three dimensional (3D) numerical methods were developed (Krishnappan and Lau, 1986; Prinos, 1990; Naot et al., 1993; Pezzinga, 1994) to reproduce turbulent structure of flow in straight compound open channels.

However, there are limited reports available concerning the investigation on meander channels with floodplains. Most of the efforts of Toebes and Sooky (Toebes and Sooky, 1966); Greenhill and Sellin (Greenhill and Sellin, 1993), Sellin et al. (Sellin and Willetts, 1993), Willetts and Hardwick (Willetts and Hardwick, 1993), Wark and James (Wark and James, 1994), and Shiono et al. (Shiono et al., 1999a) were concentrated on the energy loss, conveyance, or the stage-discharge relationship of meandering compound sections. To the knowledge of the writers there are only a few reports available (Muto, 1997); Shiono and Muto (Shiono, 1993) that describe the distribution of velocity in meandering compound channels. The present study is aimed at understanding the flow and velocity distribution in meandering compound channels and simulating the flow field using the power law. The work presented in this paper is based on the results of series of three test channels as detailed in Tables 1 and 2.

Table.1.Geometrical Parameters of Experimental Channels.

Sl No	Item Description	Channel Type		
		Type I[a]	Type II[b]	Type III[c]
1	Wave Length	60.0 cm	60.0 cm	300.0 cm
2	Amplitude	18.7 cm	20.5 cm	20.0 cm
3	Main channel width (b)	10.0cm	10.0 cm	44.0cm
4	Main channel depth (d)	10.0cm	10.0cm	25.0cm
5	Top width of the channel along with the flood plain (B)	52.5 cm	41.8± 21.3 cm[d]	138 cm
6	Wave length along channel center line	73.5cm	72.55 cm	312.76 cm
7	Slope of the channel	0.0061	0.004	0.00278
8	Minimum radius of curvature of channel centerline at bend apex	23.1cm	35.0 cm	114 cm
9	Ratio of top width (*B*) to channel width (*b*)	5.25	2.13	3.136
10	Sinuosity	1.225	1.210	1.043

**[a]Flood plain walls on both sides are straight in the down valley direction. This gives rise to unequal floodplains on either side of the meandering main channel at all locations except the geometrical cross-over.

[b]A floodplain is attached to one side of the meandering main channel. The wall of the floodplain is straight in the down val ley direction. The wall of the meandering main channel represents the other boundary of the compound channel flow zone. In the channel.

[c]Two meandering floodplains of equal widths are attached to the meandering main channel.

[d]At the first bend apex, the top width of the compound channel is 41.8 cm and at the following bend apex it is 21.3 cm. This is due to the type of geometry adopted for the channel.

Table.2. Hydraulic Conditions of Experimental Runs.

Sl. no	Channel Type	Channel Description	Depth of flow (cm)	Discharge (cm^3/s)	Series name
1	Type I	Meander with flood plain smooth	11.6	3,960	II
2	Type II	Meander with flood plain smooth	12.19	5,800	IV
3	Type III	Meander with flood plain smooth	29.5	94,535	VIII

2. EXPERIMENTAL SETUP

Details of the experimental setup and procedure concerning the flow and velocity observations in meandering channels with floodplains were reported earlier (Patra and Kar, 2000). Experiments were conducted utilizing the facilities available at the Water Resources and Hydraulic Engineering Laboratory of the Civil Engineering Department of the Indian Institute of Technology, Kharagpur, India. The geometrical parameters of the experimental channels are given in Table 1. For the three types of experimental channels (Fig. 1) the ratio ''α'' between overall width ''*B*'' and main channel width ''*b*'' are kept between 2.13 and 5.25. The observations were made at the section of maximum curvatures (bend apex) of the meander channel and also at the locations of reversal curvature (geometrical cross over). Hydraulic conditions of experimental runs are given in Table 2. Plan forms of the types of meandering experimental channels with floodplains are shown in Fig. 1. The vertical, horizontal, and diagonal plains of separation of compound channel are represented by the interface lengths aa_1 , aa, and aa_2 , respectively, whereas the interface plane aa_3 is a variable and is located by measuring an angle *u* it makes with the vertical plane aa1 (Fig. 1).

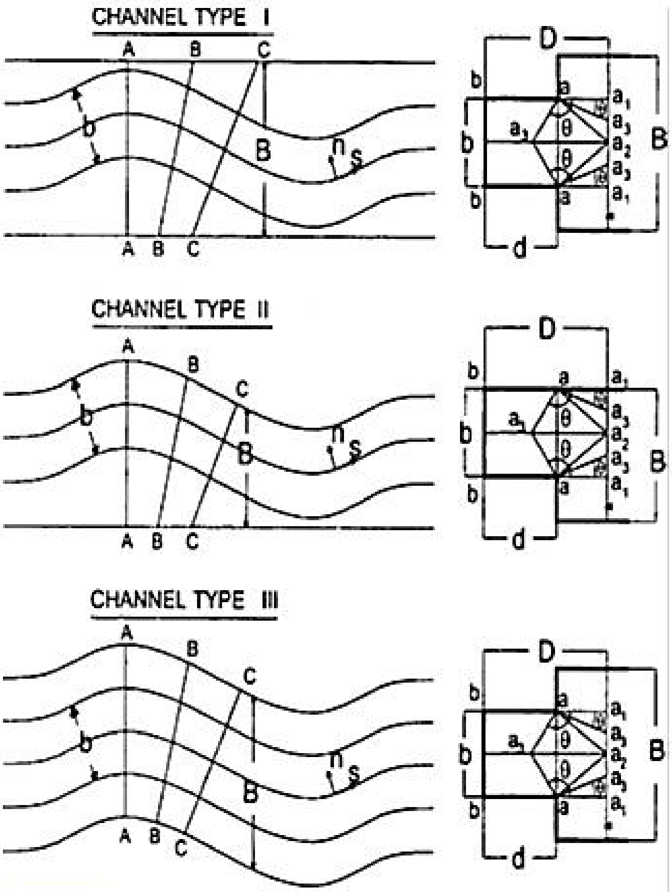

Figure 1. Plan form of types of experimental meandering channels with flood plains.

3. THEORETICAL CONSIDERATIONS

In all the types of present deep meandering channels, a sinusoidal curve has been considered to follow the channel centerline. An intrinsic coordinate system (Fig. 1) in which the s-axis along the channel centerline, positive in the stream wise direction and n-axis perpendicular to s-axis and positive away from the channel center is used. The channel bed is considered to be rigid and assumed to have no lateral slope. The channel width b is kept constant throughout. The velocity components in s- and n- directions are represented by u and v respectively.

3.1 Distribution of Tangential (Longitudinal) Velocity in Meandering Main Channel.

Ikeda and Nishimura (1986) expressed the depth averaged velocities in a simple meandering channel in terms of an unperturbed reach averaged velocity plus a quantity denoting perturbation in the channel due to curvature. For tangential velocity, the equation was expressed as

$$u_{dav} = U + u' \quad (1)$$

in which U = reach averaged tangential fluid velocity; and u' = perturbed velocity component which was modeled as

$$u' = U\frac{n}{r_{cm}}(a\ sinKs + b_1 cosKs) \quad (2)$$

in which r_{cm} = channel centerline radius of curvature at the bend apex; and a and b_1 = coefficients. For a meandering channel the centerline radius of curvature is represented by a sine generated curve represented by

$$r_{cm} = r_c \cos(Ks) \quad (3)$$

in which K = arc-length bend wave number taken as $2\pi/L$; and L=meander arc length, defined as the distance measured along the channel centerline between the repeating points. At the sidewalls, Ikeda and Nishimura's (1986) Eq. (1) does not satisfy no slip condition. For the present analysis concerning the flow in deep and mildly meandering channels, the equations are modified as

$$u_{dav} = u_{odav} + u_{1dav} \quad (4a)$$

where

$$u_{0dav} = U\frac{2p+1}{2p}\left\{1-\left(\frac{2n}{b}\right)^{2p}\right\} \quad (4b)$$

and

$$u_{1dav} = u_{0dav}\frac{n}{r_{cm}}A\sin\left(\frac{2\pi s}{L}-\sigma\right) \quad (4c)$$

in which u_{dav}= depth averaged tangential velocity at any location n in the channel; u_{0dav}=depth averaged zeroth order tangential velocity representing the parameter for the same channel in a straight reach; u_{1dav}=depth averaged first-order velocity (this quantity represents the curvature driven depth averaged velocity component); A=coefficient which depends on the channel geometry; and σ=phase angle in meandering channel. The friction parameter p is taken the same as the ‘‘power law’’ coefficient ((Zimmerman and Kennedy, 1978); (Odgaard, 1986)(Odgaard, 1989)) describing the lateral variation of zeroth-order tangential velocity. The parameter p is related to shear velocity u^* , Darcy-weisbach friction factor f and Chezy coefficient C as $p=ku_{dav}/u^*=k(8/f)^{0.5}=kC\sqrt{g}$ *(Zimmerman and Kennedy, 1978)* in which $u^*=(\tau_0/\rho)$; ρ =fluid density; and $\tau_0$bed shear stress. For open channel flow problems, the value of p varies between 3 and 7 (Odgaard, 1989). Generally the value of p is taken as 7 and the equation is known as ‘‘1/7th power law”. At the side walls, that is, for n±b/2, the equations satisfy no-slip condition. The reach averaged velocity U can be evaluated using the well-known Manning's equation

$$U = \frac{1}{n_1}R^{\frac{2}{3}}S^{\frac{1}{2}} \quad (5)$$

in which, n_1 = Manning's roughness coefficient; R = reach averaged hydraulic radius; and S=reach averaged channel slope. The phase angle σ represents the phase difference between the development, that is, the growth and decay of secondary flow and the channel curvature. As shown in Fig. 2 the discharge centerline and the channel centerline are somewhat out of phase. Zhou, Chang, and Stow (Zhou et al., 1993) had shown that the maximum curvature of flow tends to be located somewhat downstream of the bend apex (which is the location of maximum channel curvature). For shallow and weak meandering channels Zhow, Chang and Stow (1993) proposed equation for phase angle σ as

$$\sigma = \tan^{-1}\left\{\frac{\pi}{k}\left[\frac{1}{k}+\left(\frac{8}{f}\right)^{1/2}\right]\frac{d}{L}\right\} \tag{6}$$

which was improved to equation (7) by Patra and Kar (2004) as

$$\sigma = \frac{d}{b}e^{-d/b}\tan^{-1}\left\{\frac{\pi}{k}\left[\frac{1}{k}+\left(\frac{8}{f}\right)^{1/2}\right]\frac{d}{L}\right\} \tag{7}$$

in which k = Von Karrman's constant which has a value of 0.40 for clear water; d = mean flow depth; and f = friction factor. From the experimental channel runs evaluation of the coefficient A and the phase angle σ have been done subsequently. The phase

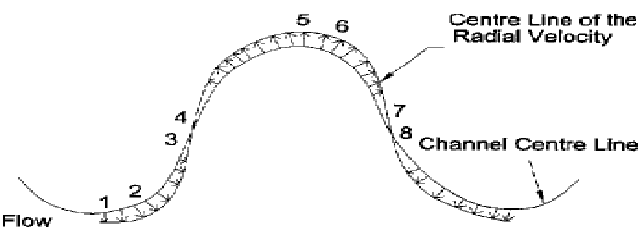

Figure 2. Spatial variation of transverse velocity in meandering channel.

3.2 *meander channel with floodplain*

For modeling longitudinal velocity in a meandering compound channel, the cross section is divided into zones of lower main channel, upper main channel, and floodplain by imaginary interface planes running from the main channel flood plain junctions (Fig. 1). On account of the availability of new data for α = 8 (Shiono et al., 1999a, Shiono et al., 1999b), Eqs.(6) and (7) of Patra and Kar (2000) are improved and the proposed equations for percentage of flow carried by the main channel $\%Q_c$ and lower main channel $\%Q_{lc}$ separated from the compound section by a vertical and horizontal interface plane respectively are given as

$$\%Q_c = \frac{100}{[(\alpha-1)\beta+1]} + 108\left(\frac{\alpha-1}{\alpha}\right)^{0.25}(3.3\beta)^{4/\alpha}e^{-9.9\beta} * \left[1+\frac{36\beta\ln\left(\frac{1}{S_r}\right)}{\delta}\right] \tag{8}$$

$$\%Q_{1c} = \frac{100}{[(\alpha-1)\beta+1]} + 300\left(\frac{\alpha-1}{\alpha}\right)^{1.75}(5.3\beta)^2e^{-15.9\beta} * \left[1+\frac{36\beta\ln\left(\frac{1}{S_r}\right)}{\delta}\right] \tag{9}$$

in which α = B/b; β = [$(D-d)/D$]; B = top width of the compound section; D = depth over main channel; δ = aspect ratio of main channel (b/d); and Sr = sinuosity of meander channel. Eqs.(8) and (9) take adequate care of the interaction effect between the flow in the main channel and that the flow in the flood plain. (Patra and Kar, 2000) discussed the effectiveness of equations for $\%Q_c$ and $\%Q_{lc}$ in their paper. Eqs. (8) and (9) can be reduced to those proposed by Knight and Demetriou (Knight and Demetriou, 1983) for straight compound channels (sinuosity=1). The equations can further be reduced to the flow condition of main channel only (zero width of floodplain! by taking α=B/b=1 and β=$(D-d)/D$=0. By doing so, the equations yield Q_c=$\%Q_{lc}$=100%, which is true for all types of channels. Using the same data that were used for the development of Eq. (8) the work is extended to model the zone averaged tangential velocity (U_c) in the main channel as

$$U_c = U\Delta_c = U\left\{1+1.08[(\alpha-1)\beta+1]\left(\frac{\alpha-1}{\alpha}\right)^{0.25}(3.3\beta)^{4/\alpha}e^{-9.9\beta} * \left[1+\frac{36\beta\ln\left(\frac{1}{S_r}\right)}{\delta}\right]\right\} \tag{10}$$

in which Δc = a dimensionless parameter. For a channel without floodplain, that is, $B = b$ and $D = d$, Eq. (10) gives $U_c = U$. From continuity equation, $U_fA_f+ U_cA_c=UA_T$, the mean velocity in the floodplain is estimated as

$$U_f = U\left\{\frac{A_T - A_c\Delta_c}{A_f}\right\} \tag{11}$$

where U_f = section mean velocity in the floodplain; A_f = area of cross section of floodplain; A_T (=A_f+ A_c) the total area of cross section of compound channel; and A_c = area of cross section of the main channel. Once the zone-averaged velocity in the main channel is obtained the depth averaged tangential velocity at a location n in the channel is modelled as

$$u_{cdav} = u_{codav} + u_{c1dav} \tag{12a}$$

Where

$$u_{c0dav} = U_c\frac{2p+1}{2p}\left\{1-\left(\frac{2n}{b}\right)^{2p}\right\} \tag{12b}$$

and

$$u_{1dav} = U_c\frac{2p+1}{2p}\left\{1-\left(\frac{2n}{b}\right)^{2p}\right\}A\frac{n}{r_{cm}}\sin\left(\frac{2\pi s}{L}-\sigma\right) \tag{12c}$$

Using power law the tangential (longitudinal) velocity can be made three dimensional in the following form:

$u_c =$

$$u_{c0dav}\frac{p+1}{p}\left\{\left(\frac{cd-z}{d}\right)\frac{z}{d}\right\}^{\frac{1}{p}} + u_{c1dav}\frac{p+1}{p}\left\{\left(\frac{cd-z}{d}\right)\frac{z}{d}\right\}^{1/p} \quad (13)$$

in which u_c = point tangential velocity at the location of n and z in the channel. Similarly, using the same data that were used for the development of Eq. (9) the work is extended to model the zone averaged velocity (U_{lc}) in the lower main channel separated from a compound section by a horizontal interface plane aa (Fig. 1) as

$$U_{1c} = U\Delta_{1c} = U\left\{\left(1+\frac{\alpha\beta}{1-\beta}\right)\left[\frac{1-\beta}{(\alpha-1)\beta+1} + 3\left(\frac{\alpha-1}{\alpha}\right)^{1.75}(5.3\beta)^2 e^{-15.9\beta} * \left[1+\frac{36\beta\ln\left(\frac{1}{S_r}\right)}{\delta}\right]\right]\right\} \quad (14)$$

in which Δlc=a dimensionless parameter and is equal to unity for a channel without floodplain, that is, $\alpha=B/b=1$ and $\beta=(D-d)/D=0$. Knowing the zone averaged velocity in the lower main channel (U_{lc}), the zone averaged velocity in the upper main channel with floodplain ($U_{u\&f}$) can be computed from the continuity equation as

$$U_{u\&f} = U\left\{\frac{A_T - A_{1c}\Delta_{1c}}{A_{u\&f}}\right\} \quad (15)$$

in which A_{lc} = area of cross section of lower main channel (marked as abba in Fig. 1); and $A_{u\&f}$ = area of cross section in upper main channel with floodplain. The depth averaged tangential velocity at a location n in the upper main channel with floodplain separated from lower main channel by an horizontal interface aa (Fig. 1) at the level of floodplain can be modeled as

$$u_{u\&f} = u_{ou\&f} + u_{1u\&f} \quad (16a)$$

$$u_{u\&f} = U_{u\&f}\frac{p+1}{p}\left\{\frac{B^2-4(n\pm x)^2}{B^2-b^2}\right\}^{\frac{1}{p}} + U_{u\&f}\frac{p+1}{p}\left\{\frac{B^2-4(n\pm x)^2}{B^2-b^2}\right\}^{\frac{1}{p}} A\frac{(n\pm x)}{(B+r_{cm})} * \sin\left(\frac{2\pi s}{L}-\sigma\right) \quad (16b)$$

in which the power law

$$u_{0u\&f} = U_{u\&f}\frac{p+1}{p}\left\{\frac{B^2-4(n\pm x)^2}{B^2-b^2}\right\}^{\frac{1}{p}} \quad (16c)$$

is used to obtain the radial distribution of depth averaged velocity across the channel cross section from the zone averaged velocity $U_{u\&f}$; x = distance between channel centerline and the centerline of the meander belt. At the floodplain sidewalls, that is, at $(n\pm x)=B/2$, Eq. (16b) satisfy the no-slip condition as the magnitude of $\{B^2-4(n\pm x)^2\}$ is zero.

A close look into the present formulations governing the distribution of depth averaged velocity across a channel section[Eqs. (4), (12), (16)] reveals that the formulations take adequate care of the effect of secondary circulation in the meandering channels. The first term of u_{dav} , that is, u_{0dav} in these equations gives a distribution of depth averaged velocity across the channel section with maximum (at n=0) at the channel centerline and zero at the side walls (for $n=\pm b/2$ or $\pm B/2$). This part of the equation represented by u_{0dav} gives a distribution of depth averaged velocity in a straight and prismatic channel. Introduction of the second term of u_{dav}, that is, u_{1dav} modifies the magnitudes of primary velocity distribution u_{dav} by taking adequate care of the effect of curvature and the phase lag. For a straight and prismatic channel, the value of u_{1dav} =0 as $r_{cm} = \infty$`. The effect of u_{1dav} is to gradually increase the values of u_{dav} toward the inner bank and decrease them proportionately toward the outer bank (with distance n measured from the channel centerline! as per the observed patterns of flow, while taking adequate care of the degree of curvature of the channel and the resulting phase lag. The present formulations take adequate care of the variation of primary velocity u, in s-, n- and z-directions resulting from the secondary circulation.

4. PROCEDURE OF ANALYSIS

4.1 *Estimation of parameters σ and A*

For application of the models, the phase lag angle σ and the coefficient A needs to be evaluated. The phase lags in simple meander channels have been obtained by measuring the distance or lag between the point of reversal curvature of the channel and the point where the depth averaged radial velocity at the channel centerline is zero. For the present channels, the minimum and maximum phase lag angles are found to be 0° and 76.5°, respectively. Results of Eq. (7) for all types of simple meander channel runs give the minimum of the standard error between the observed and estimated phase lags.

The values of coefficient A for simple meander channels are evaluated using the observed data in the following form of Eq. (4):

$$A = \left(\frac{u_{dav}}{u_{odav}} - 1\right) / \left(\frac{n}{r_{cm}}\right)\sin\left(\frac{2\pi s}{L}-\sigma\right)$$

A best fit relation between the observed A and the channel parameters (meander length L, depth-width ration d/b) for simple meander channels take the following form:

$$A = log\left(\frac{d}{L}\right)e^{d/4b} \quad (17)$$

Eqs. (7) and (17) show that the parameters σ and A are dependent significantly on the channel width, depth, and the meander arc length. Therefore incorporating the corresponding parameters concerning meandering compound channel geometry in Eqs.(7)–(17), the following modified form of equations for the estimation of σ and A for meandering compound channel results:

$$A = \frac{1}{[(\alpha-1)\beta+1]} log\left(\frac{D}{L}\right) e^{D/4B} \qquad (18a)$$

and

$$\sigma = \frac{D}{B} e^{-D/B} \tan^{-1}\left\{\frac{\pi}{k}\left[\frac{1}{k} + \left(\frac{8}{f}\right)^{1/2}\right]\frac{D}{L}\right\} \qquad (18b)$$

It is difficult to obtain the observed values of σ and A for meandering compound channels. Therefore the results of Eq. (18) could not be validated. However, it will be seen later that using the parameters σ and A [from Eq. (18)] the estimated depth averaged and point tangential velocity in meander compound sections are found to give satisfactory results.

5. DISTRIBUTION OF TANGENTIAL VELOCITY IN THE MAIN CHANNEL, LOWER MAIN CHANNEL, AND UPPER MAIN CHANNEL WITH FLOODPLAIN

With reference to Fig. 1, the main channel is defined as the area bound between a_1abbaa_1 and the lower main channel is represented by the area marked as abba. The entire cross section of the compound channel minus the area bound by abba is denoted as the upper main channel with floodplain. To obtain the distribution of tangential velocity in these regions the following steps may be followed.

a. Main Channel

1. Calculate the phase lag angle σ and the coefficient A from Eqs. (18a) and (18b);
2. Obtain the reach averaged velocity of the compound channel U from the relation Q_T / A_T , if the total discharge Q_T of the compound channel is known; and
3. If Q_T is unknown then a variable interface plane of zero shear [Eq. 7, Patra and Kar 2000] may be used to separate the compound channel section into zones, the discharge for each zone is calculated separately using Mannings equation and added up to get Q_T ;
4. Using Eq. (10), calculate the zone averaged tangential velocity in the main channel U_c ;
5. At a given location s in the meander path, use Eq. (12) to calculate the depth averaged tangential velocity u_{dav} at radial distances $\pm n$ in the channel cross section, n is measured from the centerline of the main channel. A separate value of u_{dav} is obtained for each value of $\pm n$ in the channel section; and
6. Steps (5) is repeated for other locations s in the meander path.

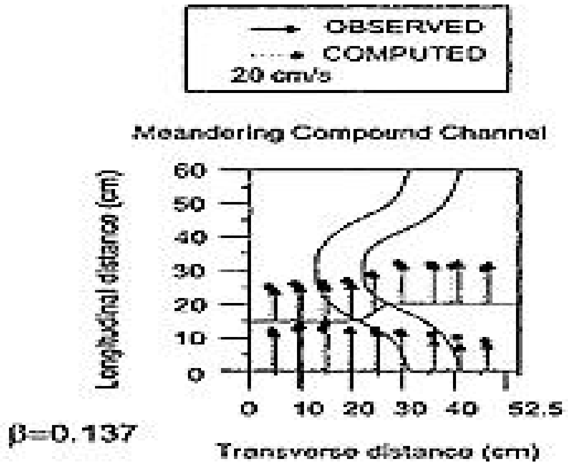

Figure 3. Distribution of depth averaged tangential velocity for meandering Type I, Series II channel.

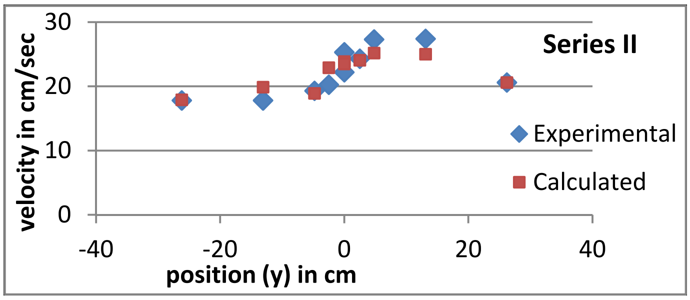

Figure 4. Radial distribution of tangential velocity for channel type I series II.

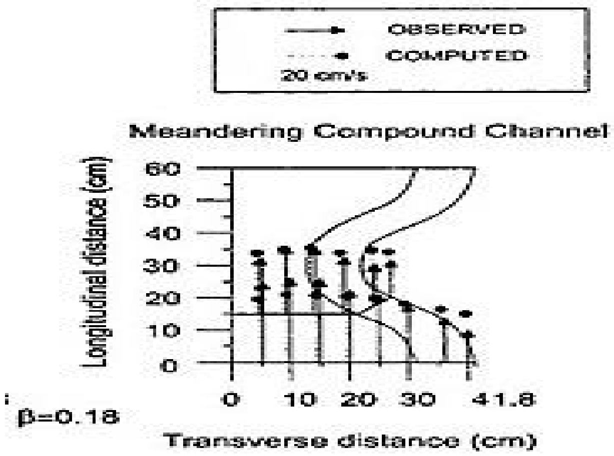

Figure 5. Distribution of depth averaged tangential velocity for meandering Type II, Series IV channel.

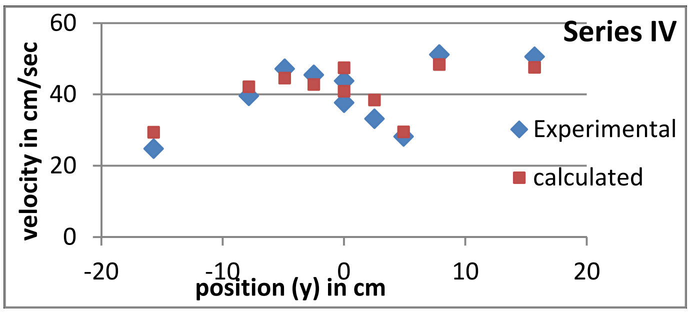

Figure 6. Radial distribution of tangential velocity for channel type II series IV.

To get the distribution of tangential velocity in the lower main channel—upper main channel with floodplain the following steps may be followed.

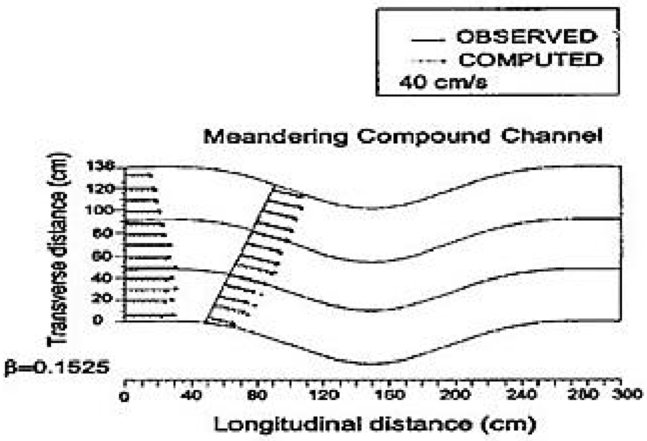

Figure 7. Distribution of depth averaged tangential velocity profile for meandering Type III, Series VIII channel.

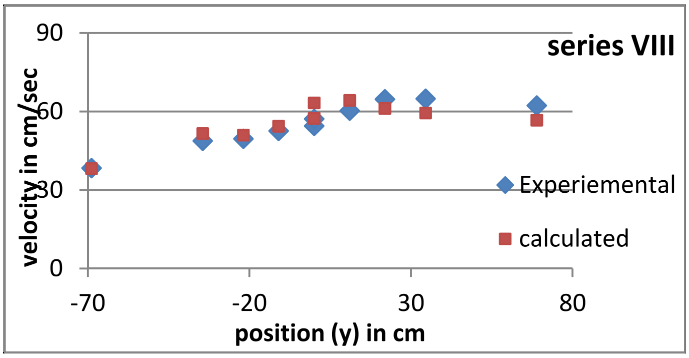

Figure 8. Radial distribution of tangential velocity for channel type III series VIII.

5.2. Lower Main Channel

1. Calculate σ, A, and U as outlined in Steps (1) through (3) as above;
2. Using Eq. (14), calculate the zone averaged tangential velocity in the lower main channel U_{lcdav} ;
3. At any given location s in the meander path, calculate the depth averaged tangential velocity u_{lcdav} at the radial distances $\pm n$ in the cross section in the lower main channel using Eq.(4). Obtain a separate value of u_{lcdav} for each value of the coordinate position n in the channel;

5.3. Upper Main Channel with Floodplain

4. Obtain the zone averaged tangential velocity in the upper main channel with floodplain from Eq. (15) with the help of U_{lc} of Step (2);
5. For a particular location s in the meander path and at various radial distances $\pm n$ in the channel cross section, calculate the values of $u_{u\&fdav}$ corresponding to every coordinate point n of the section from Eq. (16). The values of s and A are already known at Step (1) and x is scaled from the plan form geometry of meandering compound channel;

The computed depth averaged longitudinal velocities $u_{u\&fdav}$ obtained at the bend apex and also at the location of reversal curvature for the channel series II, IV, and VIII (Table 2) are compared with the corresponding observed values in Figs. 3, 5 and 7 respectively.

From the figures it can be seen that the experimental depth averaged velocities are in fair agreement with their corresponding computed values except some local variation in Fig. 5.

6. COMPARISON OF THE RESULTS OF THE PRESENT MODEL WITH THE MEANDERING COMPOUND CHANNEL DATA OF OTHER INVESTIGATORS

Shiono, Muto, Knight, and Hyde (Shiono et al., 1999a) reported the depth averaged and layer averaged velocity distribution for their meandering experimental channel with overbank flows having the following parameters; total top width B =1,200 mm, width of meander belt = 1,000 mm, bend radius r_{cm} = 425 mm, cross over angle 90°, sinuosity S_r=1.571, main channel width b=150 mm, main channel height d = 53mm and meander wave length = 1,700 mm. For the relative flow depth β[=(D-d)/D]=0.15, the channel carried a discharge (Q) of 0.002204 m^3/s with mean velocity U=0.113 m/s, whereas for β=0.50 the corresponding channel discharge and velocity were 0.01988 and 0.268 m/s, respectively. The channel had a longitudinal slope of 0.001. Using the proposed equations, the depth averaged tangential velocity distribution in the meandering main channel and floodplain of the compound section are calculated for the channel of Shiono et al (Shiono et al., 1999a, Shiono et al., 1999b) and plotted in Fig. 9 along side the corresponding reported values at the bend apex and also at the location of geometrical cross over for comparison. However the computed values of u_{dav} in the upper main channel with floodplain are found to be slightly higher than the observed values.

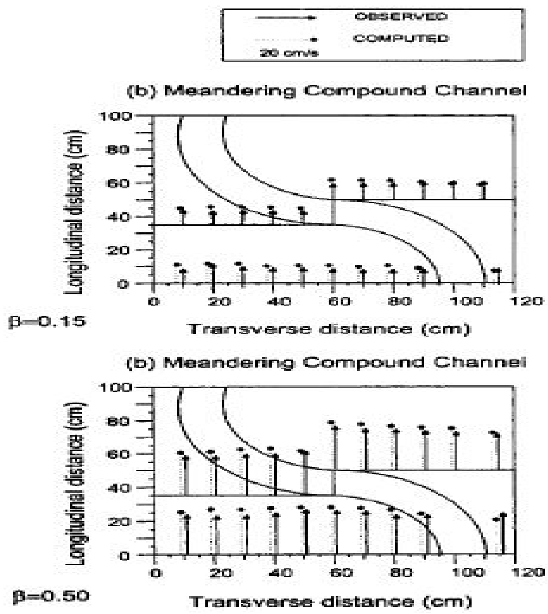

Figure. 9. Depth averaged and layer averaged tangential velocity profile of channel of Shiono et al. (1999a) for β=0.15 and β=0.50

Table.3. Distribution of Depth Averaged Tangential Velocity u_{dav} in main channel, Lower Main Channeland Flood plain of the compound section at bend apex.

location	Close to n=+$b/2$		n=+b/4		n=0		n=-b/4		Close to n=+$b/2$	
	observed	estimated	observed	estimated	observed	estimated	observed	estimated	observed	estimated
Channel Type-I, Series-II, Lower Main Channel										
Series II	27.3	25.18	24.3	24.05	22.2	23.5	20.25	22.9	19.3	18.9
Channel Type-I, Series-II, Flood plain										
Series II	**20.6**	**20.6**	**27.4**	**25**	**25.3**	**23.86**	**17.8**	**19.87**	**17.8**	**17.9**
Channel Type-II, Series-IV, Lower Main Channel										
Series IV	**28.2**	**29.5**	**33.2**	**38.45**	**37.7**	**40.9**	**45.5**	**42.8**	**47.2**	**44.58**
Channel Type-II, Series-IV, Flood Plain										
Series IV	**50.6**	**47.6**	**51.2**	**48.4**	**43.8**	**47.48**	**39.6**	**42.15**	**24.8**	**29.4**
Channel Type-III, Series-VIII, Lower Main Channel										
Series VIII	**64.7**	**61.2**	**60.3**	**64.3**	**54.5**	**63.3**	**52.6**	**54.4**	**49.6**	**42.4**
Channel Type-III, Series-VIII, Flood Plain										
Series VIII	**62.3**	**56.7**	**64.9**	**59.46**	**57.2**	**57.4**	**48.8**	**51.6**	**38.2**	**38.4**

7. CONCLUSIONS

On the basis of present investigation concerning flow in deep and rigid meandering channels with and without floodplains, the important conclusions drawn are as follows:

1. The phase lag angle between the channel geometry and the flow geometry can be modelled adequately using Eq.(18).
2. Using the modelled phase lag angle, the depth averaged tangential (longitudinal) velocities in the meandering channel as well as in the meandering compound channel are obtained which are given in the table(3) as well as shown in the fig(4),(6),(8) respectively .

REFERENCES

Abril, J. B. & Knight, D. W. (2004) Stage-discharge prediction for rivers in flood applying a depth-averaged model. *Journal of Hydraulic Research,* 42, 616-629.

Bhattacharya, A. K. (1995) Mathematical model of flow in meandering channel. PhD thesis, IIT, Kharagpur, India.

Das, A. K. (1984) A study of river floodplain interaction and boundary shear stress distribution in meander channel with one side floodplain. PhD thesis, Indian Institute of Technology, Kharagpur, Kharagpur, India.

Greenhill, R. K. & Sellin, R. H. J. (1993) Development of a simple method to predict discharges in compound meandering channels. *Proceedings of the ICE-Water Maritime and Energy,* 101, 37-44.

Ikeda, S. & Nishimura, T. (1986) Flow and bed profile in meandering sand-silt rivers. *Journal of Hydraulic Engineering,* 112, 562-579.

Kar, S. K. (1977) A study of distribution of boundary shear in meander channel with and without floodplain and river floodplain interaction. PhD thesis, Indian Institute of Technology, Kharagpur, Kharagpur, India.

Knight, D. W. & Demetriou, J. D. (1983) Flood plain and main channel flow interaction**.** *Journal of Hydraulic Engineering,* 109, 1073-1092.

Knight, D. W. & Hamed, M. E. (1984) Boundary shear in symmetrical compound channels. *Journal of Hydraulic Engineering,* 110, 1412-1430.

Knight, D. W. & Stokes, N. (1996) Refined calibration of a depth-averaged model for turbulent flow in a compound channel. *Proceedings of the ICE-Water Maritime and Energy,* 118, 151-159.

Krishnappan, B. G. & Lau, Y. L. (1986) Turbulence modeling of flood plain flows. *Journal of Hydraulic Engineering,* 112, 251-266.

Lin, B. & Shiono, K. (1995) Numerical modelling of solute transport in compound channel flows. *Journal of Hydraulic Research,* 33, 773-788.

Lotter, G. K. (1933) Considerations on hydraulic design of channels with different roughness of walls. *Trans. All Union Sci. Res., Inst. Hydraul. Eng,* 9, 238-241.

Mera et al.(2012) Turbulence anisotropy in a compound meandering channel, River Flow 2012.

Muto, Y. (1997) Turbulent flow in two-stage meandering channels. The University of Bradford.

Naot, D., Nezu, I. & Nakagawa, H. (1993) Hydrodynamic behavior of compound rectangular open channels. *Journal of Hydraulic Engineering,* 119, 390-408.

Naot, D. & Rodi, W. (1982) Calculation of secondary currents in channel flow. *Journal of the Hydraulics Division,* 108, 948-968.

Odgaard, A. J. (1986) Meander flow model. I: Development. *Journal of Hydraulic Engineering,* 112, 1117-1135.

Odgaard, A.J. (1989) River-meander model. I: Development. *Journal of Hydraulic Engineering,* 115, 1433-1450.

Patra, K. C. & Kar, S. K. (2000) Flow interaction of meandering river with floodplains. *Journal of Hydraulic Engineering,* 126, 593-604.

Pezzinga, G. (1994) Velocity distribution in compound channel flows by numerical modeling. *Journal of Hydraulic Engineering,* 120, 1176-1198.

Rozovskii, I. L. (1957) *Flow of water in bends of open channels*, Academy of Sciences of the Ukrainian SSR.

Sellin, R. H. J. & Willetts, B. B. (1993) Behaviour of meandering two-stage channels. *Proceedings of the ICE-Water Maritime and Energy,* 101, 99-111.

Shiono, K. (1993) Secondary flow structure for inbank and overbank flows in trapezoidal meandering compound channel. *Proc. 3rd Symp. on Refined Flow Modelling and Turbulence Measurements.*

Shiono, K., Al-Romaih, J. S. & Knight, D. W. (1999a) Stage-discharge assessment in compound meandering channels. *Journal of Hydraulic Engineering,* 125, 66-77.

Shiono, K. & Knight, D. W. (1990) Mathematical models of flow in two or multi stage straight channels. *Proc. Int. Conf. on River Flood Hydraulics.*

Shiono, K., Muto, Y., Knight, D. W. & Hyde, A. F. L. (1999b) Energy losses due to secondary flow and turbulence in meandering channels with overbank flows. *Journal of Hydraulic Research,* 37, 641-664.

Thomas, T. G. & Williams, J. J. R. (1995) Large eddy simulation of turbulent flow in an asymmetric compound open channel. *Journal of Hydraulic Research,* 33, 27-41.

Toebes, G. H. & Sooky, A. A. (1966) Hydraulics of meandering rivers with flood plains. American Society of Civil Engineers.

Tominaga, A. & Nezu, I. (1991) Turbulent structure in compound open-channel flows. *Journal of Hydraulic Engineering,* 117, 21-41.

Wark, J. B. & James, C. S. (1994) An application of new procedure for estimating discharge in meandering overbank flows to field data. *2nd Intl. Conf. on River Flood Hydraulics.*

Wark, J. B., Samuels, P. G. & Ervine, D. A. (1990) A practical method of estimating velocity and discharge in compound channels. *River flood hydraulics*, 163-172.

Willetts, B. B. & Hardwick, R. I. (1993) Stage dependency for overbank flow in meandering channels. *Proceedings of the ICE-Water Maritime and Energy,* 101, 45-54.

Wormleaton, P. R., Allen, J. & Hadjipanos, P. (1982) Discharge assessment in compound channel flow. *Journal of the Hydraulics Division,* 108, 975-994.

Zhou, J., Chang, H. H. & Stow, D. (1993) A model for phase lag of secondary flow in river meanders. *Journal of Hydrology,* 146, 73-88.

Zimmerman, C. & Kennedy, J. F. (1978) Transverse bed slopes in curved alluvial streams. *Journal of the Hydraulics Division,* 104.