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EVALUATION OF BOUNDARY SHEAR DISTRIBUTION IN A MEANDERING CHANNEL

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***Abstract**: Information on the nature of boundary shear stress distribution in simple and meandering open channel are required to solve a variety of river hydraulics and engineering problems so as to get a basic understanding of the flow resistance relationship, calculation of energy losses, understanding the mechanism of sediment transport, design of stable channels, revetments etc. Distribution of boundary shear stress depends mainly on the channel geometry and the structure of the secondary flow cells. In a meandering channel, the complex flow mechanism causes significant variation in the distribution of shear around its wetted perimeter. Therefore, evaluation of boundary shear stress distribution at various locations of the wetted perimeter gives a better insight into the problem. Literature shows that the investigators have studied the boundary shear distribution mostly for shallow channels having low sinuosity. Reports on boundary shear distribution for deep and highly meandering channels are limited. The work presented in this paper is based on series of highly meandering channels having distinctly different sinuosity and geometry. The three dimensional flow velocities at a number of pre defined grid points across the channel section close to the surface are measured using 16-Mhz Micro ADV (Acoustic Doppler Velocity-meter). Using these velocity data, the shear stress at various points on the channel boundaries are evaluated from semi log plot of velocity distribution as well as by Preston tube technique. Based on the experimental results, this paper predicts the distribution of boundary shear in meandering channels thus showing the interrelationship between the boundary shear, sinuosity and geometry parameters. The models are also validated using the well published data of other investigators.*

***Keywords**: Boundary Shear; Sinuosity; Aspect Ratio; Meandering Open Channel.*

INTRODUCTION

Distribution of boundary shear stress around the wetted perimeter of a channel is influenced by many factors, notably the shape of the cross-section, the longitudinal variation in plan form geometry, the sediment concentration and the lateral and longitudinal distribution of boundary roughness. All of these factors combine to make the prediction of the local shear stress at any point on a channel boundary a difficult task.

It is a great challenge to the river engineers and researchers working in the field to predict the distribution of wall shear stress (τ_b) around the wetted perimeter of a given

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channel for a certain flow-rate. Leighly (1932) proposed the idea of using conformal mapping to study the wall shear stress in open-channel flows. He pointed out that, in absence of secondary currents, the wall shear stress acting on the bed must be balanced by the downstream component of the weight of water contained within the boundary. Einstein's (1942) hydraulic radius separation method is still widely used in laboratory studies and engineering practice. Knight and Macdonald (1979), Knight (1981), Noutsopoulos and Hadjipanos (1982), Knight et al. (1984), Patel (1984) and Hu (1985) have led to an improved understanding of the lateral distributions of wall shear stress in straight prismatic channels and ducts. Patra (1999), Khatua (2008) reported the boundary shear stress distribution in meandering channels of different sinuosity. This paper draws on the distribution of boundary shear stress along the wetted perimeter of meandering open channel flow under sediment-free conditions. Equations are presented for the percentage of the total shear force which acts on the walls of a meandering channel of different geometry and sinuosity.

EXPERIMENTAL SETUP AND PROCEDURE

The present work is based on the authors present data observed using the experimental meandering channels at NIT Rourkela and also from the IIT Kharagpur, India. Out of the four channels fabricated at NIT Rourkela, the present paper is based on the two types of channels (Table 1) for which the verified data are available.

Table 1. Geometry Parameters of the Experimental Meandering Compound Channels

Sl. No	Item Description	Mildly Meander Type-I channel	Highly Meander Type-II channel
1.	Wave length in down valley direction	400 mm	2185 mm
2.	Amplitude	162 mm	685 mm
3.	Geometry of main channel section	Rectangular	Trapezoidal (side slope 1:1)
4.	Main channel width (*b*)	120 mm	120mm at bottom
5.	Bank full depth of main channel	120 mm	80 mm
6.	Top width of compound channel (*B*)	577 mm	1930 mm
7.	Slope of the channel	0.0031	0.0053
8.	Meander belt width (B_W)	443 mm	1650 mm
9.	Minimum radius of curvature of channel centerline at bend apex	140 mm	460 mm
10.	Ratio of top width (*B*) to channel width (*b*) = (α)	4.808	16.083
11.	Sinuosity(S_r)	1.44	1.91
12.	Cross over angle in degree	104	102
13.	Flume size	0.6m×0.6m×12m	2.0m×0.6m×12m

A recirculation system of water supply is established with pumping of water from an underground sump to an overhead tank from where water could flow under gravity to a stilling tank. From the stilling tank water is led to the experimental channel through a baffle wall, and a transition zone helped reduce turbulence of the water flow. An adjustable tailgate at the downstream end of the flume is used to achieve uniform flow over the test reach in the channel for a given discharge. Water from the channel is collected in a volumetric tank for measuring the flow discharge, from where water runs back to the underground sump, thus establishing a closed circuit of flow. The measuring devices consist of a point gauge mounted on a traversing mechanism to measure flow depths having a least count of 0.1 mm. Point velocities are measured using the three probes of 16-Mhz Micro ADV (Acoustic Doppler Velocity-meter having least count of 0.001 m/s) at a number of points across the predefined channel section. Photo 1 and Photo 2 shows experimental channels with measuring equipments.

Photo 1. **Type-I Experimental Channel Photo**

2. Type-II Experimental Channel

As the ADV is unable to read the data of upper most layer (up to 5 cm from free surface), a micro-Pitot tube of 4 mm external diameter is used. Detailed skeleton of the probes limits are shown in Fig. 1. Using the data of velocities close to the surface of the channels, the boundary shear at various points on the channel bed at the predefined channel sections are evaluated from the logarithmic velocity distribution relationship. The meandering channel sections are using Perspex sheets that are considered as smooth having Manning's roughness coefficient n = 0.001 found from stage-discharge relationship of straight channel of same materials.

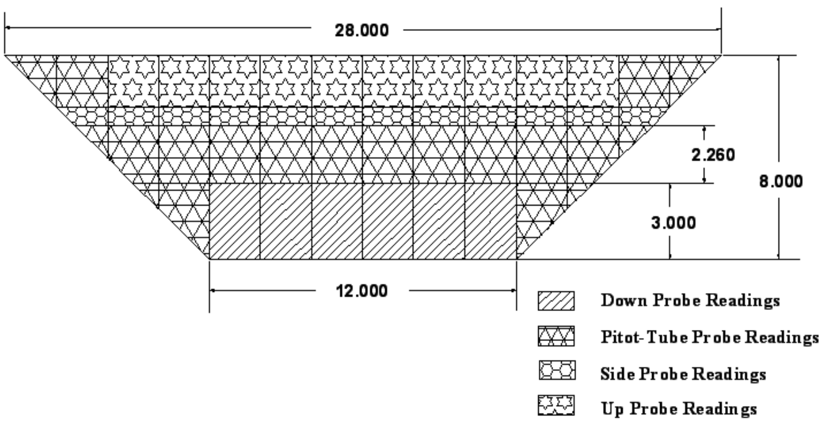

Fig. 1. Detailed Skeleton of the Probes Limit

A detailed longitudinal velocity and boundary shear distribution are carried out for the meandering channels of Type-I and Type-II having sinuosity 1.44 and 1.91 respectively. Measurements are taken at the bend apex where the radius is maximum curvature effect (Fig. 2a, b).

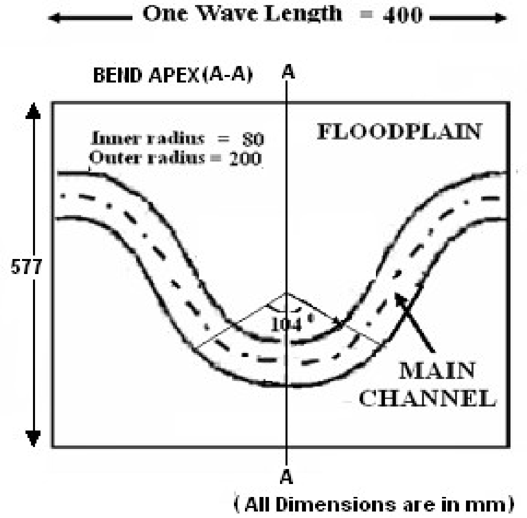

Fig. 2. (a) Location of Bend Apex (A-A) of Type-I Meandering Channel

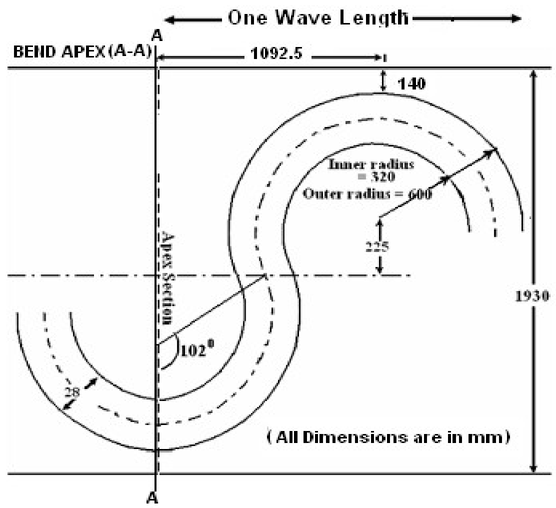

Fig. 2. (b) Location of Bend Apex (A-A) of Type-II Meandering Channel

DISTRIBUTION OF TANGENTIAL (LONGITUDINAL) VELOCITY

Radial distribution of tangential velocity in contour form for the meandering channel of Type-I at bend apex is shown in Fig. 3. Similarly for Type-II channel the radial distributions of tangential velocity at bend apex is shown in Fig. 4. Figs. 3 and 4 also show the boundary shear distribution for the two types of channels.

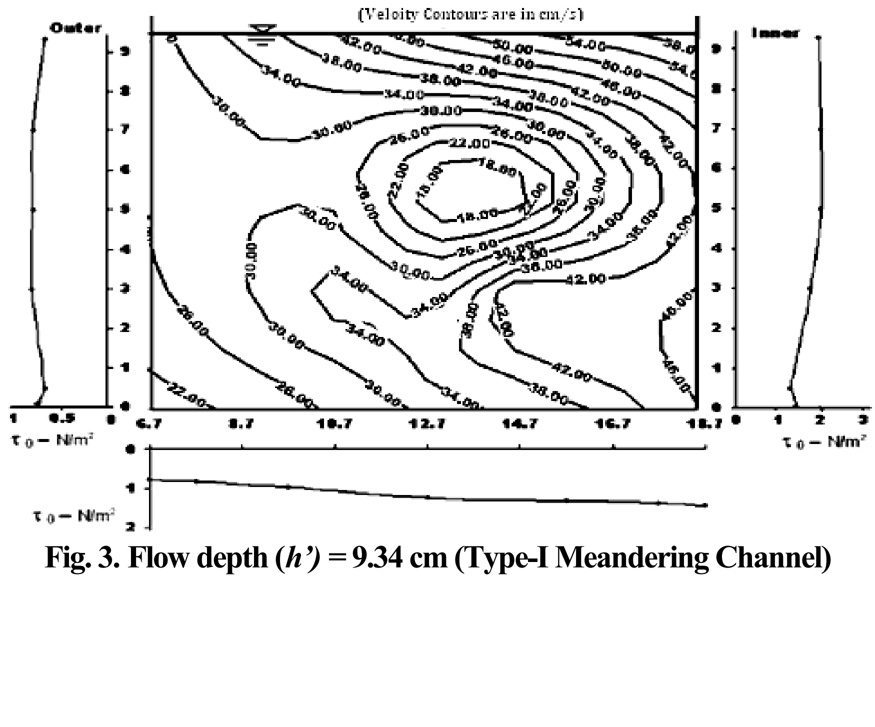

Fig. 3. Flow depth (*h'*) = 9.34 cm (Type-I Meandering Channel)

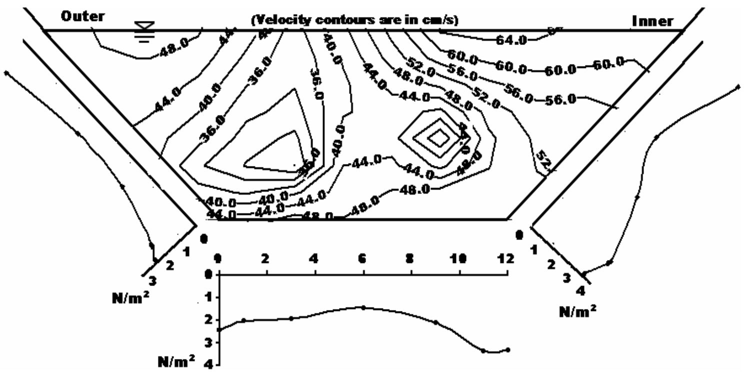

Fig. 4. Flow depth (*h'*) =7.33 cm (Type-II Meandering Channel)

DISTRIBUTIONS OF BOUNDARY SHEAR FORCE

The three-dimensional flow structure in a meandering channel leads to the complicated pattern of boundary shear stress distribution that becomes more complicated when the channel sinuosity increases. One line of approach to predict the distribution of boundary shear around the wetted perimeter of a given channel for a certain flow rate is from the theoretical approach, concerning a detailed knowledge of the distribution of numerous turbulence coefficients. The other one is to adopt an empirical approach, fitting equations to the data obtained. The second approach has been attempted by many investigators such as Knight and Hamed (1984), Knight and Patel (1985), Patra (1999) and Khatua (2008). Works of some of the previous investigators such as are like Ghosh and Roy (1970), Myers (1978) and Noutsopoulos and Hadjipanos (1982), etc for smooth rectangular channels, Patel (1984) and Rhodes (1991) for smooth rectangular duct, in smooth trapezoidal channels with 45° side walls slope, and with uniformly roughened trapezoidal channels are worth mentioning. They have used experimental data either for uniformly roughened or smooth trapezoidal channels, where the total shear force carried by the walls (SF_W) are found to follow a systematic reduction with increase in aspect ratio ($\alpha = b/h$), where *b* is base width and *h* is flow depth. The percentage of the total shear force carried by the walls ($\%SF_W$) is an useful parameter, defined as

$$\%SF_W = (100\, SF_W)/SF \tag{1a}$$

where *SF*= total shear force. Similarly, the percentage of the total shear force carried by the channel bed ($\%SF_B$) is given as

$$\%SF_B = (100 SF_B)/SF \tag{1b}$$

where $\%SF_B$= percentage of shear force carried by the base and *SF*= total shear force. Knight *et.al* (1984) showed that for a straight channel the percentage of shear in wall SF_W varied exponentially with the aspect ratio [i.e.($\alpha = b/h$)]. It can be expressed as

$$\%SF_w = e^m \tag{2}$$

where *m* is a function related to the aspect ratio($\alpha = b/h$) of the channel. By plotting separately on a log-log scales and assuming a simpler linear relationship between $\%SF_W$ and aspect ratio *(α = b/h)*, we can write

$$\log_{10}(\%SF_w) = 1.4026 \log_{10}\left(\frac{b}{h} + 3\right) + 3 + 2.67 \quad (3)$$

where *b* is base width and *h* is depth of water. Comparing Eqs. (2) and (3) we have

$$m = 2.30259\,[A_1 Log_{10}\left(\frac{b}{h} + A_2\right) + A_3] \quad (4)$$

that gives

$$m = -3.23 Log_{10}(\alpha + 3) + 6.146 \quad (5)$$

It proves that *m* is a function of the aspect ratio [i.e. m = F (*b/h*) = F (α)].

Analysis of Boundary Shear Results in Meandering Channels

For meandering channel, the distribution of shear is more complicated when compared to that of a straight channel. For the present analysis, the published meandering channel data of Patra (1999) along with the current meandering channel data are used. Patra (1999) provided shear force data of two types of meandering channel having smooth and rough surfaces having sinuosity (S_r) of 1.21 and 1.22 and aspect ratios varying from α =1.01 to 2.45. The difference value ($\%SF_W$) between the straight channel using Eq.(3) and the observed ($\%SF_W$) for experimental meandering channels are compared with the dimensionless geometrical parameters like aspect ratio (α) and sinuosity (S_r). Now for the four types meandering channels having sinuosity of 1.21, 1.22, 1.44 and 1.91, the variation of difference factor of wall shear (DF) with aspect ratio and sinuosity are shown in Fig. 5 and Fig. 6 respectively.

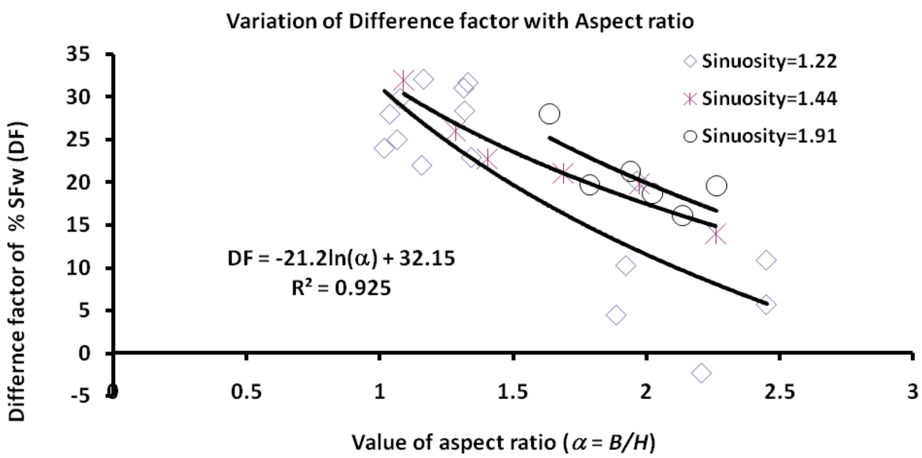

Fig. 5. Variation of Difference Factor of Wall Shear with Aspect Ratio

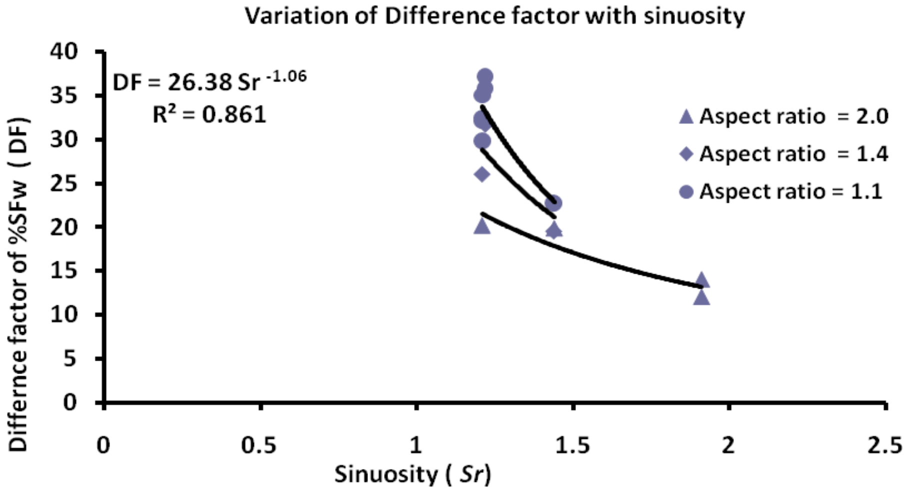

Fig. 6. Variation of Difference Factor of Wall Shear with Sinuosity

From Fig. 5 and Fig. 6 it is clear that difference factor of wall shear increases with channel aspect ratio (α=*b/h*) and decreases with sinuosity (*Sr*), which is the most significant parameter influencing the flow mechanism in meandering channels. The best fit functional relationships of the difference factor with the parameters obtained from the plots in Fig. 5 and Fig. 6 is given as

Difference factor = $F_1(S_r^{-1.06})$ and $F_2 \ln(30.692 \times \alpha)$ (6)

where F_1 is the function of sinuosity (*Sr)* and F_2 is the function of aspect ratio *(α)*. Combining all the dependable parameters the difference factor is composited as

$$\text{Difference factor} = 2.15 S_r^{-1.06} Ln(30.692 \times \alpha) \tag{7}$$

Equation (1) is further modified to incorporate meandering effect and is written as

$$\%SF_W = e^m + 2.15 S_r^{-1.06} Ln(30.692 \times \alpha) \tag{8a}$$

where $m = -3.23 Log_{10}(\alpha + 3) + 6.146$ (8b)

The variation of computed percentage of wall shear force using equation (8a), along with the observed values for Type-I, Type-II channels along with the two meandering channels of Patra (1999) is shown in Fig. 7. The variation of error in the computation of (*%SF_W*) by the proposed equation (8a) against different channel aspect ratio are plotted in Fig. 8 giving the least error. Figs. 7 and 8 show the adequacy of the developed equation.

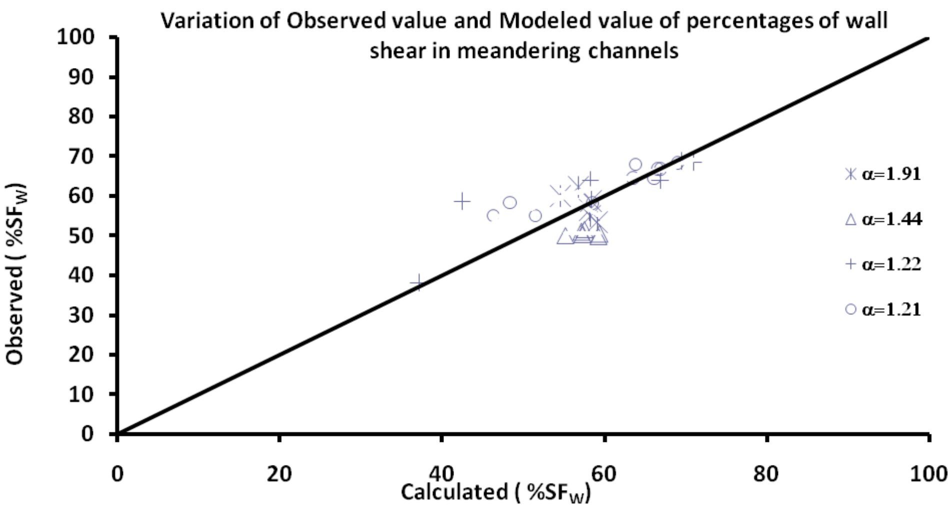

Fig. 7. Variation of Observed and Modeled Value of Wall Shear in Meandering Channel

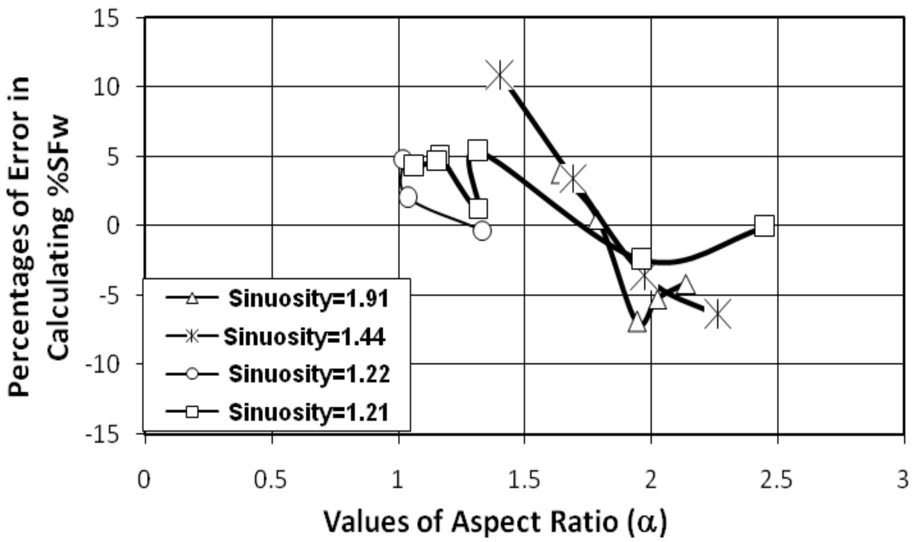

Fig. 8. Percentage of Error in Calculating %SF$_W$ with Values of Aspect Ratios

CONCLUSIONS

- Experiments are carried out to evaluate the boundary shear from point to point for meandering channels of different aspect ratio and sinuosity are studied. The overall mean value of wall shear stress obtained through the velocity gradient approach and Preston tube technique compares well with that obtained from energy gradient approach. The results examine the effect of channel sinuosity and cross section geometry on the wall shear distribution in meandering channels. The study is also extended to a meandering channel of higher sinuosity (S_r = 1.91).

- Comparing the results of wall shear stress distribution of meandering channel with straight channel, it can be seen that there is asymmetrical nature of shear distribution especially where there is predominant curvature effect. Maximum value of wall shear occurs significantly below the free surface and is located at the inner walls (Figs. 3 and 4).

- The wall shear distribution in meandering channel is also found to be the function of dimensionless parameters such as aspect ratio and sinuosity. An equation (8) has been developed to predict the wall shear distribution in meandering channel. The developed equations give least error for the present meandering channels.

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