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An experimental study of shear stress distribution in a compound meandering channel

Abdullah Al Amin[1, *], S. M. Khan[2], Ashraf-ul-Islam[3]

[1]Bangladesh Water Development Board, Dhaka, Bangladesh
[2]Dept. of Water Resources Engineering, BUET, Dhaka, Bangladesh
[3]RDRS, Dhaka, Bangladesh

Email address:
amin_01buet@yahoo.com(A. A. Amin), mostafakhan@wre.buet.ac.bd(S. M. Khan), ashraf.hiz@gmail.com(Ashraf-ul-Islam)

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Abstract: Naturally river flow can be characterized as compound meandering channel in which the shear stress characteristics are quite intricate. Reliable investigation of shear stress distribution in a compound meandering channel is essential in solving a variety of river hydraulics and engineering problems, designing stable channels and bank protection, understanding the mechanism of sediment transport. A laboratory experiment has been conducted in a compound meandering channel with symmetric cross-sections having floodplain width ratio of 1, 1.67, 2.33, 3 and depth ratio of 0.20, 0.30, 0.35, 0.40 using the large-scale open air facility in the Department of Water Resources Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. Point velocity data have been collected using an ADV (Acoustic Doppler Velocity Meter) for different depth and width ratio at different locations of a compound meandering channel. Shear stress is calculated from the Prandtl-Von Karman Universal Velocity Distribution Law. The laboratory experimental investigation reveals that shear stress increases with the increase of depth and width ratio and low magnitude of boundary shear is observed in the outer bend as compare to the inner bend in a compound meandering channel.

Keywords: ADV, Depth Ratio, Flood plain, Meandering Channel, Shear Stress Distribution, Width Ratio

1. Introduction

Most of the rivers have their cross sectional geometry in the form of a compound section where a deep main channel is often flanked by one or two shallow adjacent floodplains. The main channel flow is usually faster and the floodplain flow is slower comparatively. When the flow goes over bank, such a combination generates considerable momentum and mass transfer between floodplain flow and main channel flow rendering the flow analysis an extremely complex task. Additionally if the planform or the path of the channel is sinuous or meandering instead of straight one which is the case more often than not, further complex mechanisms occur in the channel flow such as large sets of coherent vertical structures due to presence of secondary flow of Prandtl's 1st kind as well as due to anisotropic turbulence arising out of complex geometry of the channel and uneven bottom topography. The determination of suitable stage discharge relationship and the associated flow variables such as depth averaged velocity and boundary shear are often hard to achieve due to strong three dimensional nature of the flow where no complete theoretical analysis is possible. River flow can be schematized as compound meandering channel in which the mechanism of erosion in the outer bank and deposition in the inner bank. Naturally, River overflow their banks during the episodes of high flooding resulting in a huge potential damage to life and property as well as erosion and depositions of sediments. In a compound meandering channel there is an intense interaction between the faster moving main channel flow and slower moving floodplain flow resulting in a lateral transfer of a significant amount of longitudinal momentum which affects the shear stress distribution in a channel flow. Shear stress in a compound meandering channel is strongly governed by interaction between flow in the main channel and that in the floodplain due to prevailing of different hydraulic conditions in the main channel and floodplain flow, 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.

The flow structure of a compound channel is a complicated process due to the transfer of momentum between the deep main channel and the adjoining shallow floodplains. Experiments are carried out to measure the shear stress around the wetted perimeter of a two-stage compound channel and to quantify the momentum transfer in terms of shear stress along the assumed interfaces originating from the junction between main channel and flood plain. This is further helpful for deciding appropriate interface plains for evaluation of accurate stage-discharge relationship for a compound channel of all geometry. The lateral momentum transfers are found to magnificently affect the shear stress distribution in flood plain and main channel sub sections [1]. Knowledge of momentum transfer to different interfaces can be acquired from the distribution of boundary shear in the sub sections. In the present work, commonly used equations of shear stress distributions across assumed interface plane are analyzed and tested for various types of compound channels and their flow conditions using published data. Furthermore, a modified expression to predict the boundary shear distribution in compound channels that is good for all width ratios is derived and is found to provide significant improved results [1].

The shear stress distribution in the straight compound channel and the compound meandering channel have been investigated by a number of authors[1],[2],[3], [4], [5], [6],[7],[8],[9],[10],[11],[12] and [13]. Most of hydraulic formulae derived by the author assuming that the shear stress distribution is uniform over the wetted perimeter. Distribution of shear stress mainly depends upon the shape of the cross section and the structure of the secondary flow cells. However, for meandering channel there is a wide variation in the local shear stress distribution from point to point in the wetted perimeter. Also the magnitude of shear in a meandering channel is significantly different from that of straight channel having the same geometry, shape and cross sectional area. For the meandering compound channels the important parameters effecting the shear stress distribution are sinuosity (S_r), the amplitude (a), relative depth (D_r), width ratio (W_r) and the aspect ratio (A_r) [13]. Information regarding the shear stress distribution is crucial in controlling floods, solving a variety of river hydraulics and engineering problems, designing stable channels, revetments and artificial waterways. Considering the importance of shear stress distribution in a channel flow, there is a need to evaluate the shear stress carried by the main channel and floodplain boundary in a compound meandering channel at various locations of meander path. The aim of this study is to describe the effect of the interaction mechanism on the basis of shear stress distribution in compound meandering channel sections with varying floodplain width and depth ratio.

2. Methodology

The experimental study has been conducted in the open air facility of Water Resources Engineering Department, Bangladesh University of Engineering and Technology (BUET), Dhaka. The experimental setup is shown in theFig.1 which consists of two parts, the permanent part and the temporary part. The permanent part is the experimental facility necessary for the storage and regulation of water circulating through the experimental reach. The temporary part is mainly brick walls which are used to vary the floodplain width for different setups. The experimental reach consists of a 670 cm long symmetric compound meandering channel, set at constant bed slope (S_o) of 0.001845 with fixed bed and banks and sinuosity ratio (S_r) of 1.20.Water is drawn by the centrifugal pump of discharge capacity 80 l/s from the storage reservoir then it discharges into the u/s reservoir and coveys water to the experimental reach through approach channel of 30m in length and 3.1m in width. To ensure a more smooth flow towards the approach channel guide vanes and tubes are placed between the upstream reservoir and the approach channel which are at right angle to each other. In order to prevent turbulence in the approach channel, PVC pipes (Diffuser) are used. The water regulating function of the downstream end is provided by tail gate. The tail gate rotates around a horizontal axis. It is operated to maintain desired water level in the experimental reach. At the end of the experimental channel, water is allowed to flow freely so that backwater has no effect in the experimental reach. Behind the tail gate, the water falls into the stilling basin and passes through a transition flume which allows water for recirculation.

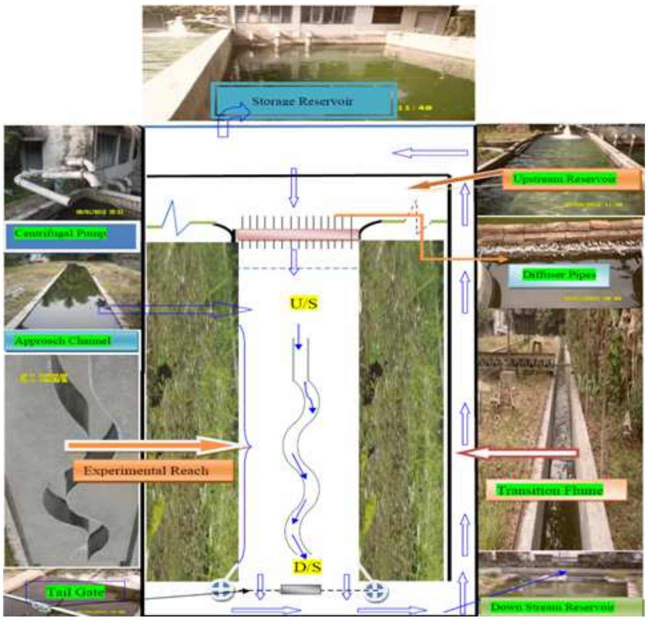

Figure 1. Schematic diagram of the laboratory experimental setup.

Experiments were performed for four cases i.e. width ratio 1, 1.67, 2.33,3 at four runs i.e. depth ratio Dr =0.2, 0.3, 0.35, 0.4.

Case1: It represents no floodplain condition having width ratio Wr =1 and cross-sectional dimension of the Channel is 45.7cmx42cm.

Case2: It indicates symmetric floodplain width 15.3 cm having width ratio Wr =1.67. The cross-sectional dimension of the main channel is 45.7cmx24.5cm, left floodplain 15.3cm x18 cm and right floodplain 15.3cm x18 cm.

Case3: It indicates symmetric floodplain width 30.5 cm having width ratio Wr=2.33. The cross-sectional dimension of the main channel is 45.7cmx24.5cm, left floodplain 30.5cm x18 cm and right floodplain 30.5cm x18 cm.

Case4: It indicates symmetric floodplain width 45.70 cm having width ratio Wr=3. The cross-sectional dimension of the main channel is 45.7cmx24.5cm, left floodplain 45.7cm x18 cm and right floodplain 45.7cm x18 cm.

Point velocities data have been collected by ADV (Acoustic Doppler Velocity meter) at different locations (u/s clockwise bend, u/s crossover, u/s anticlockwise bend etc) of a compound meandering channel. Each location is divided into 19zones starting from left floodplain to right floodplain. The main channel is equally divided into nine zones (zone 1 to zone9), the left floodplain is equally divided into 5zones (zone1 to zone5) and right floodplain is divided into 5 zones (zone1 to zone5). The definition sketch of compound meandering channel is shown in Fig. 2 and the experimental run conditions are shown in the table 1.

Table 1. *Experimental run conditions.*

Case	Run no.	Width Ratio (Wr)	Depth Ratio (Dr)	Location of the Reading
I	1	1.0	0.2	Velocity reading at 0.1H, 0.2H, 0.4H, 0.6H, 0.8H from the water surface in the main channel and 0.1H', 0.2H', 0.4H',0.6H', 0.8H' from the water surface in the flood plain
	2		0.3	
	3		0.35	
	4		0.4	
II	5	1.67	0.2	
	6		0.3	
	7		0.35	
	8		0.4	
III	9	2.33	0.2	
	10		0.3	
	11		0.35	
	12		0.4	
IV	13	3.00	0.2	
	14		0.3	
	15		0.35	
	16		0.4	

In each zone 3D point velocity readings are taken by ADV at five vertical points i.e. 0.1H, 0.2H, 0.4H, 0.6H, 0.8H for main channel and 0.1H',0.2H', 0.4H', 0.6H', 0.8H' for floodplain. Sample of data collection by ADV is shown in the Fig. 3. In each vertical point 60 seconds point velocity readings are taken and average velocity of 60 seconds point velocity is used for plotting the velocity profile. Shear stress is calculated by Prandtl-Von Karman Universal Velocity Distribution Law from the observed velocity profile and the toal shear stress for each cross-section is calculated by the equation (2). The shear stress of the channel section is calculated as follows

$$\frac{U}{U^*}=\frac{1}{K}\ln\left(\frac{Z}{Z_0}\right) \qquad (1)$$

Where U is the mean velocity, U* is the friction velocity, k is von Karman's constant (k=0.4), Z is the height above bed, Z_0 is the height of hydraulic roughness.

$$\tau o=\rho gRS_0 \qquad (2)$$

Where, g=gravitational acceleration, ρ= density of flowing fluid, R= hydraulic radius of the channel cross-section, S_0=channel bottom slope.

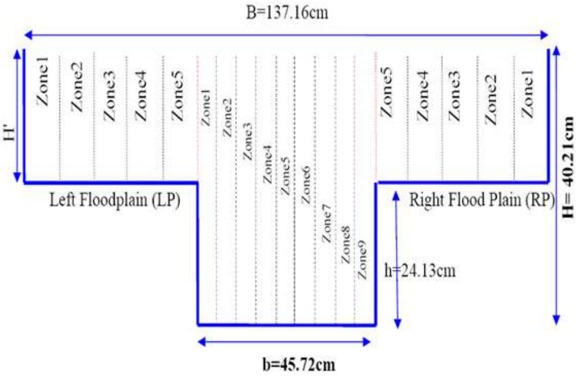

Figure 2. *Sketch of the compound meandering channel section.*

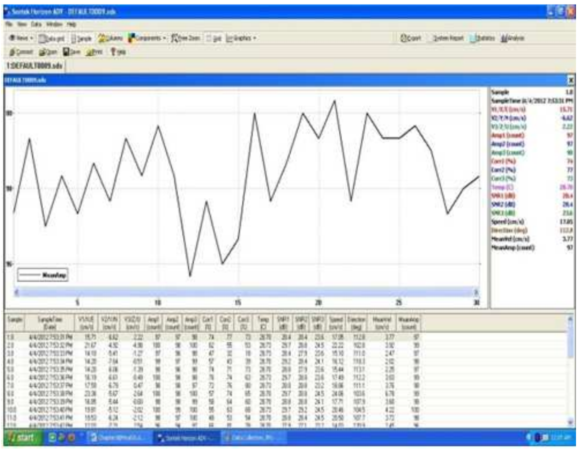

Figure 3. *Data collection by ADV.*

3. Results and Discussions

Shear stress distribution curves with varying width ratios at u/s clockwise bend section are presented in the Fig. 4, Fig. 5 and Fig. 6 and the variation of shear stress in terms of depth and width ratio are presented in the Fig.7 and Fig.8. From the observation of shear stress distribution curve, it is seen that the shear stress increases with the increase of depth and width ratio. Because shear stress depend on the hydraulic radius as well as velocity distribution of a channel section. Hydraulic radius increases with the increase of depth and width ratio. With increase of depth ratio, velocity increases and the correspondingly shear stress increases. In a compound meandering channel, the shear stress is increasing and decreasing in the inner and outer bend respectively. The maximum value of shear stress occurs along the inner bend of the main channel at low water depth ratio. But for higher depth ratio, the maximum shear stress occurs along the inner bend of the floodplain. Because at low over bank depths, the slow moving flow in the floodplain interact with the fast moving main channel intensely and considerable momentum exchange takes place giving rise to large non uniformity in the longitudinal velocity distribution. As the depth ratio increases, the intensity of interaction diminishes considerably.

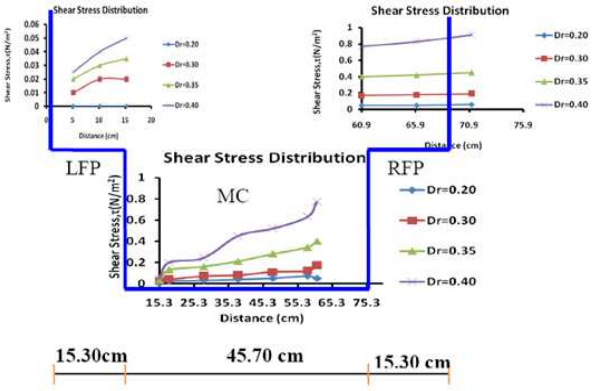

Figure 4. Shear Stress Distribution at u/s bend section for Wr=1.67.

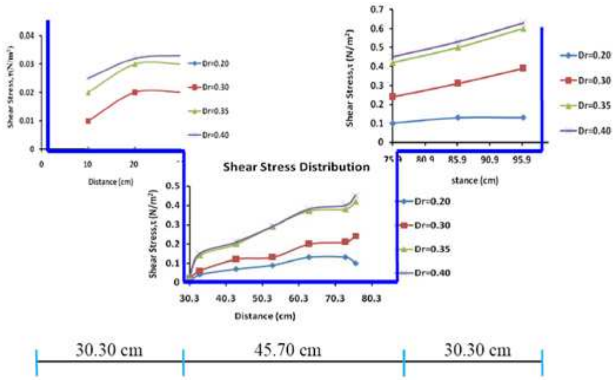

Figure 5. Shear Stress Distribution at u/s bend section for Wr=2.33.

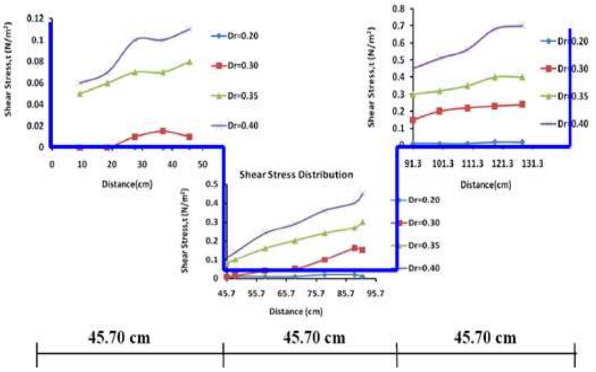

Figure 6. Shear Stress Distribution at u/s bend section for Wr=3.00.

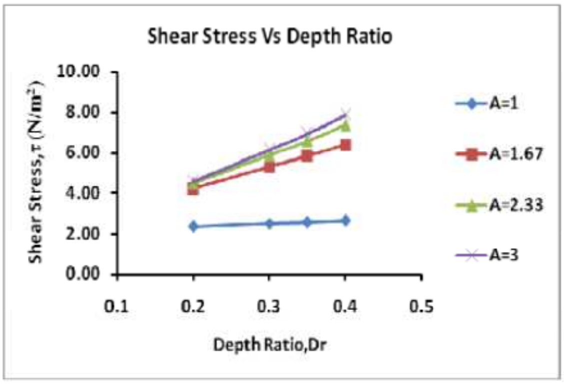

***Figure 7.** Variation of Shear Stress with respect to Depth Ratio.*

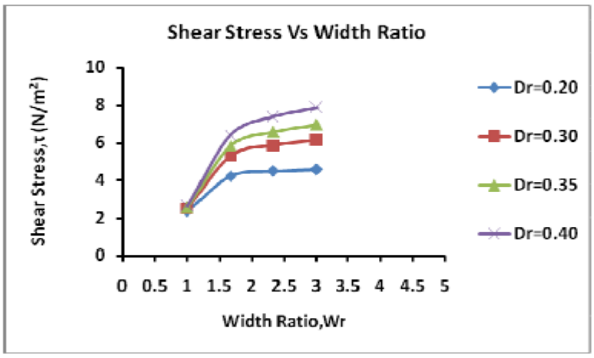

***Figure 8.** Variation of Shear Stress with respect to Width Ratio.*

4. Conclusions

A series of laboratory experiments have been conducted in a symmetrical compound meandering channel with different floodplain width to investigate the geometry effect on the shear stress distribution in the main channel and floodplains due to the momentum transfer between the deep section and floodplains. On the basis of present research concerning the shear stress distribution in a compound meandering channel with varying floodplain width the following conclusions are drawn:

For all cases shear stress increases with the increase of depth ratio and width ratio. But the increasing rate of shear stress is higher with the depth ratio in comparable to width ratio. Low magnitude of boundary shear stress is resulted in the outer bend as compare to the inner bend of a compound meandering channel. At low water depth ratio, the maximum value of shear stress occurs along the inner bend of the main channel. But for higher depth ratio, the maximum shear stress occurs along the inner bend of the floodplain.

It is recommended that further investigation be focused on extending the present analysis to the compound meandering channel of unsymmetrical cross sections with different floodplain width.

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Nomenclature

The following symbols are used in this paper
a= amplitude
B= top width of compound meandering channel
b= width of main channel
D_r=depth ratio (H-h)/h
g=gravitational acceleration
H= total water depth
H'= depth of water above floodplain bed
h= height of the main channel
k = von Karman's constant
ρ= density of flowing fluid
R= hydraulic radius of the channel cross-section
S_o= bed slope
S_r = sinuosity ratio
U = mean velocity
U* = friction velocity
W_r = width ratio [B/b]
Z =height above bed,
Z_o = height of hydraulic roughness.

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