Estimation of Turbulent Shear stress in Gravel- bed streams: An Experimental Study

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Abstract— ***In gravel bed streams, the turbulent flow characteristics are strongly influenced by the non-homogeneity of the bed topography. The time-averaged flow characteristics close to the bed are spatially heterogeneous. To overcome this, conceptually the time averaging of Navier-Stokes equations are supplemented by spatial area averaging in the plane parallel to the average bed. To study the spatially-averaged (SA) turbulence characteristics in flows over a gravel bed, a uniform flow is created over the bed. Nortek's Vectrino four-receiver Acoustic Doppler velocimeter (ADV) probe was used to measure the instantaneous three-dimensional velocity components at the groove. Velocity distributions below the roughness crest level fairly matches with a third-degree polynomial series. In the near-bed region the Reynolds shear stresses (RSS) undergo a damping because of a diminishing level of turbulence.***

Index Terms— ***Gravel bed streams, Turbulent flow, Acoustic Doppler velocimeter, Reynolds shear stress.***

I. INTRODUCTION

Reynolds shear stresses commonly termed as turbulent shear stress offer an appropriate tool for evaluating bed shear stress and shear velocity. In theory, the bed shear stress and hence the shear velocity is estimated from the bed slope. Also, the shear velocity can be obtained from RSS distributions. Straight lines are drawn from the maximum water depth to the point of maximum Reynolds shear stress near the bed to intersect the mean bed level. The intersection of Maximum RSS with the mean bed level gives the bed shear stress. Spatial averaging of flow quantities provides realistic values in the estimation of RSS value. [3] first applied the concept of spatial-averaging (SA) method to study the structure of turbulence in an open-channel flow over a vegetation canopy. It consists of averaging the Navier–Stokes equations in time and space over an area contained in a plane parallel to the flow direction. Spatial heterogeneity in the mean flow quantities on account of bed geometry heterogeneity are the main aspect of this method. Later, [6] illustrated the advantages of the spatial-averaging methodology over conventional approaches and highlighted its potential for studying flows over very rough beds. They described the velocity distribution near the bed, especially in the layer below roughness tops within the interfacial sub layer. They observed two types of behavior. The first type is consistent with the exponential equation, whereas the second type is consistent with the linear equation. Indeed, the linear velocity distribution extends, in some cases, down to the roughness troughs, thus covering the whole interfacial sub layer. The data also support the assumption that the linear velocity profile should be applicable for flows with various degree of relative submergence. [7] Observed that the ratio between the form-induced shear stresses and frictional velocity just below the top of the roughness elements increases with decreasing relative submergence. It is shown that this phenomenon is not due to an increase in magnitude of the spatial fluctuations but rather to their correlation. This was interpreted as a result of a different adjustment of the flow around the roughness elements. [1] investigated the spatial heterogeneity of near bed flows over rough gravel-beds using the double-averaging methodology and reported that spatial flow heterogeneity is negligible at greater distances to the roughness tops and increases with decreasing height above the roughness tops. Maximum values of form induced stresses were observed below the absolute maximum of measured bed elevations. [4a] analysed the double-averaged TKE budget and reported that within the roughness layer ($z < z_c$), double-averaged velocity vanishes to zero more rapidly and this may be due to the rapid decrease in roughness geometry function when entering the interfacial layer. From the experimental data they observed that the double-averaged turbulence production, turbulent transport, and dissipation terms reach their maximums away from the reference plane ($z = 0$). [4b, 2] observed that due to flow heterogeneity induced by the bed topography, the flow is not locally uniform in the near-bed region, and a double-averaging methodology was applied over a length scale much greater than the gravel size. They also reported that the maximum turbulent kinetic energy (TKE) production occurs very close to $z = 0$. Also they have concluded that the double averaged TKE production is roughly 75% greater than the dissipation rate at the point of maximal TKE production. But limited works so far been taken up to focus on the nature of velocity fluctuations at lowest bed level to the roughness crest and its influence on other turbulent flow characteristics such as velocity distribution, Reynolds shear stress and spectral density which is objective of the present study. In particular, the researchers have taken significant attempts to represent the issue but there remains further scope of exploration. Advancement of technology and flow measuring techniques provides a new impetus to represent the effects of bed roughness on flow characteristics.

II. EXPERIMENTAL PROCEDURE

Experiments were conducted in the Water Resources Engineering Laboratory, Department of Civil Engineering, National Institute of Technology, Agartala. The flume spanned a total length of 14 m with a depth of 0.60 m and a width of 0.45 m. Uniform gravels of median size d_{50} = 40 mm was laid homogeneously in five layers to prepare a permeable gravel-bed stream. To achieve uniform flow condition in the flume, the flow depth was controlled by gates at the downstream end of the flume. The experiment was run for a flow depth of 0.14 m (measured from the mean bed level) and a mean flow velocity of 0.21 m/s. The ADV was used for measuring the flow velocity and fitted sufficiently away from the downstream gate. The water was supplied to the flume from a tank having a total capacity of 3500L. The tank was fed with two Nos. of recirculation 5 HP mono-block pumps. The water from the overhead tank flows into the flume over a triangular notch having a notch angle of 60^{o} with height 0.30 m and top width 0.35 m. The V-notch enables the measurement of quantity of water passing onto the flume. At the receiving end, the flume has a ditch packed with gravel to reduce the impact of falling water. The water then flows through the strainer which helps reduces the disturbances in the flow. The photograph of the flume with gravel bed is shown in Figure 2.

Fig.1 Experimental set-up

A 4-beam down looking Vectrino probe (Acoustic Doppler type) manufactured by Nortek was used to measure the instantaneous velocity components. It acted with an acoustic frequency of 10 MHz and a sampling rate of 100 Hz was set for the measurement. The measuring location was 5 cm below the probe. Thus the influence of the probe on the measured data was negligible. However the limitation of the probe was that the measurement was not possible with in the flow zone 5 cm below the free surface. The sampling duration of 300 s was considered ensuring a statistically time independent average velocity. The data was collected along the centre line of the flume at a working section identified 9 m downstream of the inlet. The readings were taken at the crest, lee and groove of gravels. Velocity fluctuations were recorded at various vertical distances 1 mm apart. A total of 65, 51 and 35 readings were taken at the groove, lee and crest respectively.

III. RESULTS AND DISCUSSION

The normalized stream-wise velocity u^+ above the crest level and in the groove is presented in Fig 2a. Above the crest level, the velocity profile follows universal log-law whereas; the velocity profile below the crest level deviated from the logarithmic profile due to the direct influence gravel roughness. The velocity decreases to zero near the virtual bed level and further to negative values and thereafter increases to zero near the mean bed level. To plot the data within the wall-shear layer (z > 0) above the gravel crests, the time-averaged velocity and depth are scaled by shear velocity (u_*) and Δz, respectively, such that $u^+ = \bar{u}/u_*$ and $z^+ = (z+\Delta z)/\Delta z$, where Δz = Nikuradse zero-plane displacement. To plot the experimental data, the log law was considered, as expressed in the following form:

$$u^+ = \frac{1}{\kappa}\ln\left(z^+\right) \quad (1)$$

Where κ = Von Karman coefficient. In general, Δz is taken as 0.25d_{50} and κ as 0.41.

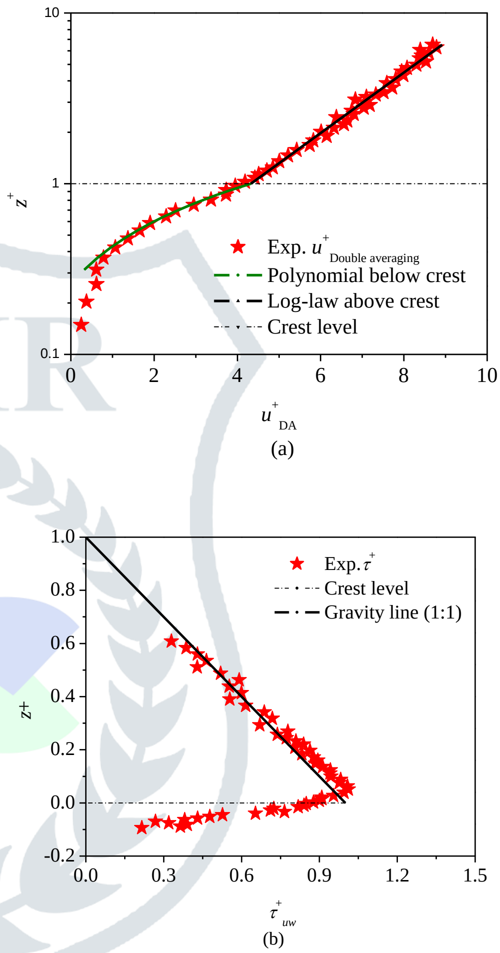

Fig. 2 Vertical distributions of (a) dimensionless double-averaged velocity distributions and (b) dimensionless double-averaged RSS distributions

The shear velocity (u_*) is obtained from τ_{uw} profile as $u_* = (-(\overline{u'w'}))^{0.5}$. The log law for u^+ within the wall-shear layer above the gravel crests (z^+> 1) is therefore given by:

$$u^+ = 2.439\ln z^+ + 4.325 \quad (2)$$

On the other hand, the profile u^+ below the crest level ($z^+ \leq$ 1) fairly matches with a third-degree polynomial series given by:

$$u^+ = 2.0367 + 10.343z^+ + 5.3019z^{+2} - 4.3504z^{+3}$$

It is in conformity with [2] that the flows above the gravel crests (z^+ > 1) and within the interfacial sub layer ($z^+ \leq 1$) correspond to the log and the polynomial law, respectively. The vertical distribution of normalized turbulent shear stress uw^+ (= $-\overline{u'w'}/u_*^2$) is shown in fig. 5.2(a-b). In the near bed region ($\hat{z}$ < 0.2, where $\hat{z}$ = z/h) the shear stress attains a maximum and then reduces towards the bed. In the upper flow zone, they are reasonably consistent with the linear law. Shear velocity u_* obtained from $-\overline{u'w'}$ distributions are compared with the values obtained from logarithmic Law, and bed slopes. From the plots of Reynolds shear stresses by double-averaging methodology, it is observed that the shear stress attains a maximum value just above the crest level and then decreases linearly with distance from the bed. A line drawn from the water surface through the maximum shear stress makes an intercept at the crest level which is equal to the bed shear stress, τ_0 and collapse on the gravity line.

Table 1 Bed shear stress, τ_b and shear velocity, u_* obtained from τ_{uw}

Location	τ_b	u_*
Crest	9.5	3.08
Groove	9.2	3.03
Lee	9.5	3.08

Table 2 Comparison of Bed shear and shear velocity

From Slope		From RSS	
u_* (m/s)	τ_{slope}	u_* (m/s)	τ_{RSS}
0.029	0.00084	0.03	0.00092

IV. Conclusions

The turbulent characteristics over rough bed were studied experimentally. Time averaged stream-wise velocity, Reynolds shear stresses, bed shear stress and statistical analysis of velocity fluctuations were studied and compared with double averaging methodologies and some important findings are summarized below:

- The velocity distribution in the outer layer was similar to that for flows over hydraulically smooth beds as stated by Nezu and Nakagawa 1993.
- In the region below the crest level the velocity profile deviated from the logarithmic profile due to the direct influence of the roughness elements.
- The velocity decreased to zero near the virtual bed level and further to negative values and thereafter increased to zero near the mean bed level. This is evident to the presence of rotational flows below the virtual bed level in the grooves.
- Reynolds shear stress attains a maximum value just above the crest level and then decreases linearly with distance from the bed. A line drawn from the water surface through the maximum shear stress makes an intercept at the crest level which is equal to the bed shear stress.
- The spectral data showed no significant deviations at various horizontal locations. The spectral data was then analyzed at various vertical distances. No significant variations were observed but three clear sub-ranges were observed.

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