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Scaling of wall shear stresses in emergent, sparse and rigid vegetated open channel flows with rough bed interior of the vegetation patch

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Abstract: **-- In this study, scaling of dominant Reynolds shear stress within the vegetation patch is performed. To simulate such flows, an emergent and sparse vegetation patch is prepared using acrylic cylindrical rods with regular spacing in streamwise and lateral directions. The vegetation patch is placed in the middle cross-section of the open channel flume. Three-dimensional flow velocities interior of the vegetation patch are measured using a Nortek Vectrinoplus Acoustic Doppler Velocimeter. The measurements are taken along the centerline in the vegetation patch. The dominant Reynolds shear stress (RSS) interior of the vegetation patch is found to be less than the vegetation-free fully developed flow. In addition, RSS values are decreasing in the downstream direction within the vegetation patch although there is a similarity in the shape of RSS profiles. The decrease in flow rate in the downstream direction along the centerline is responsible for the decrease in RSS values. There found to be a bandwidth in which all RSS values near the bed are contained. In the similarity analysis, the RSS profiles scaled such that non-dimensional RSS profiles collapse on each other. The similarity of non-dimensional RSS profiles is attempted in the paper. Scaling demonstrates wake effect, velocity defect, disturbance in the boundary layer and etc.in addition to highlighting the typical behavior of RSS profiles in any general emergent vegetation flows.**

Index Terms - Open channel flow, Emergent vegetation patch, ADV, Reynolds shear stress, Scaling.

1.0 INTRODUCTION

In this study, we performed analysis of important turbulent features at upstream, interior and downstream of a sparse vegetation patch in an open channel turbulent flow. Velocities were measured with an ADV down looking probe along stream wise, lateral and vertical directions. The vegetation patch placed in the middle cross section of the open channel flume.

The emergent vegetation patch is made by seventy uniform rigid acrylic cylindrical rods together with regular spacing between two cylinders along stream wise and lateral directions. Emergent vegetation in open channel flow affects mass and moment transfer, roughness, sedimentation, velocity of flow, bed shear, turbulence quantities, biological processes and roughness aquatic life.
Additionally, flow through emergent vegetation is characterized by significant velocity gradients and drag discontinuity at the interface resulting in shear layer formation between the vegetation stems and flow outside the vegetation.A number of experimental (prototype and laboratory) and computational studies on the mean fully-developed flow and the turbulence characteristics through emergent and over submerged vegetation of infinite length are available.

Turbulent open-channel flow over rough beds is a subset of turbulent boundary layers with two notable characteristics, namely,
(1) Flow can be defined as an equilibrium turbulent boundary layer using the asymptotic invariance principle; and

(2) This class of flows has been reported to deviate from the wall similarity hypothesis, whereby turbulent motions above the near-wall layers are independent of surface condition.

An equilibrium turbulent boundary layer is one in which the solutions exhibit self-similarity and the boundary-layer equation does not show dependence on the streamwise (x) coordinate. By defining the equilibrium solution based on the asymptotic invariance principle (AIP) (George and Castillo (1997)), it is assumed that all velocities, turbulent length scale and the pressure gradients maintain the same x dependence in order for the conditions to be equilibrium. Mixed scaling includes scaling in both logarithmic and outer layer. Nepf and Vivoni (2000) performed the experiment in open channel flume with model vegetation to understand how vegetation impact flows.

2.0 EXPERIMENTAL METHODOLOGY:

Experimental Flume Design:
Experiments were conducted in a recirculating flume of width 0.91m, length 12m and depth 0.7m with very mild

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longitudinal slope. To ensure structural rigidity for the water pressure when the flume is in operation, the flume was strengthened with toughened glass of thickness 10 mm. The flume was located on a fixed steel frame structure with hollow sections and designed to reduce the stresses on the glass when the flume was operational. A tail gate was provide at downstream end of the flume to control the flow depth.

Measuring Equipment:

A three-dimensional (3D) Acoustic Doppler Velocimeter (ADV) with four down looking probes was used to measure the point velocity across the entire channel cross-section. This type of current meter uses an acoustic pulse emitted from a central emitter and then, through a configuration of three acoustic sensors, the reflected acoustic pulse is detected and therefore the Doppler shift is measured for a particle within the flow. From these velocimeters the data were transmitted via a conditioning module to the PC where the data were interpreted to give the instantaneous Cartesian co-ordinate velocity components at a specific point in the flow.

The ADV measures the velocity components in three directions: i.e. the stream-wise (u), transverse (v), and vertical (w) directions. Measurement duration of 2 minutes was used and the measurement frequency was set to 100 Hz. To obtain measurements near to the bed sidewall boundaries and the water surface, the maximum number of points velocity measurements were taken, with downward-looking probe head.

Depth measurements were made using a pointer gauge, which had a graduated millimeter scale attached. The pointer was first set to the bed level at each point, and the scale zeroed. Then the depth was measured by moving the pointer to the free surface.

Fig 1: Experimental Set Up

Model of Vegetation Patch

The test section starts from a point 700 cm from the flume entrance and is 300 m long. The vegetation patch was located at the middle of the test section. To make the bed rough circular marbles of diameter 2.5cm were fixed at the patch base and over them vegetation rods were planted. The vegetation type adopted here were emergent, sparse and rigid. These rigid vegetation were made by uniform acrylic cylindrical rods of diameter 0.64cm and height 30cm. The rods were fixed perpendicularly as an array of 7x10 on a Perspex sheet which was fixed to channel bed. They were placed at at uniform streamwise gap of 9cm and lateral gap of 4cm.

Velocities measurements were taken at steamwise distances X= 0cm, 50cm, 80cm, 95.5cm, 113.5cm, 131.5cm, 140.5cm, 149.5cm, 167.5cm, 185.5cm, 220cm, 240cm, 285.5cm, 300cm. At each streamwise sections lateral measuring points considered were 16.7cm, 35.4cm, 39.4cm, 43.4cm, 47.4cm, 51.4cm, 55.4cm and 74.3cm from the left wall of flume. Point 47.4cm in the mid point of the cross-section.

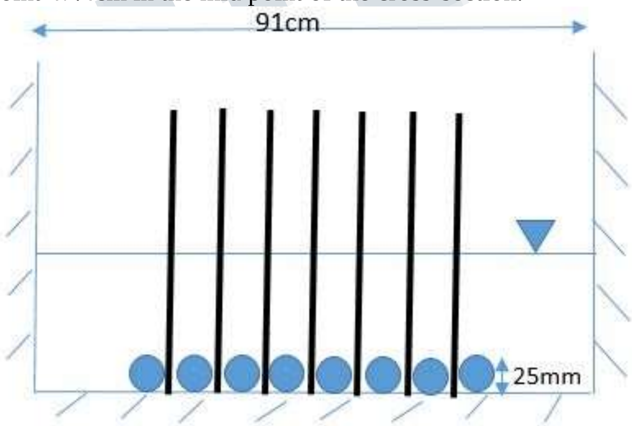

Fig 2: cross-section along lateral direction

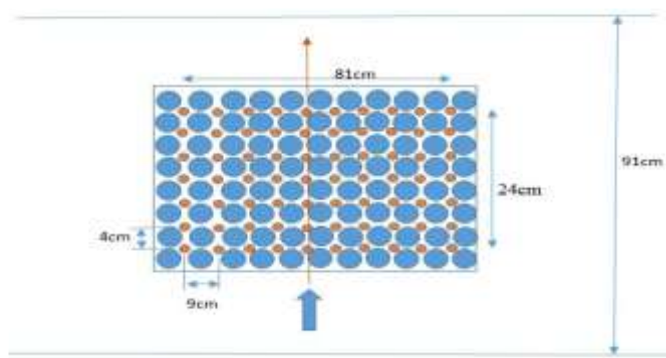

Fig 3: Top view of flume for the narrow simple channel in lateral direction

Post Processing and Correction of Data

A three-dimensional coordinate system has been adopted where x, y and z denoted streamwise, transverse and vertical

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directions respectively for the post processing of data obtained from the ADV. Spike filtering, correction and signal-to-noise ratio (SNR) thresholding techniques were used to minimize the effect the Doppler noise in the data. To further improve the accuracy of the turbulence measurements, low SNR and low correlations were removed. The spikes in velocity measurements removed from the raw time series were replaced by applying cubic polynomial interpolation following the basic ideas of Goring and Nikora (2002).

EXPERIMENTAL CONDITIONS

Flow depth	15cm
Average flow velocity	29cm/s
Maximum flow velocity	30cm/s
Reynolds Number	43500
Vegetation patch length	81cm
Vegetation patch width	24cm
Number of cylinders	70
Diameter of cylinders	0.64cm
Height of cylinders	30cm
c/c spacing of cylinders: x	9cm
y	4cm
Vegetation density	0.0178/cm

3.0 SCALING ANALYSIS

In this study, a length scale is proposed to normalize velocity profiles for vegetated open channel flow with rough bed. In open channel flow, large scale roughness could be represented by gravels, submerged vegetation or dunes. Flow over such a rough bed may differ considerably from those over smooth boundaries. Case of emergent vegetation has been considered in this study. Presence of vegetation obstructs the flow and reduces the flow velocity. Scaling is done for collapsing of the profiles that were measured under different flow conditions and hence to find out a standard distribution type of the profile. To normalize different profiles, some length scales are proposed and checked whether they normalize the profiles as desired.

EXPERIMENTAL RESULTS AND DISCUSSION

In this study, scaling has done along the lateral directions at various locations which are (16.7, 35.4, 39.4, 43.4, 51.4, 55.4, 74.3) in cm measured left side of the flume in emergent sparse vegetation patch. Out of those locations 16.7 and 74.3 are outside of the vegetation patch, remaining is within the vegetation patch.

Seven velocity profiles were observed along the lateral section of the vegetation patch by normalizing vertical height in y-direction (z/h) and normalizing streamwise(u), lateral(v), vertical(w) velocity in x-directions.

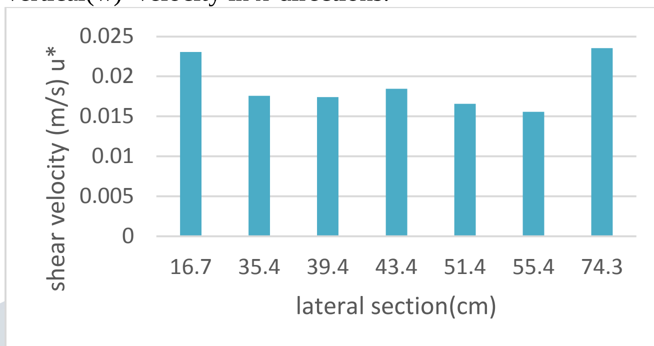

Fig.4Shear velocity inside the vegetation patch along the lateral direction

Variation of shear velocity we can see various locations in the vegetation patch is show in figure(4) above. By the above figure it is clearly shown that shear velocity is maximum at out side of vegetation patch along the lateral directions and shear velocity decrease slightly inside the vegetation patch

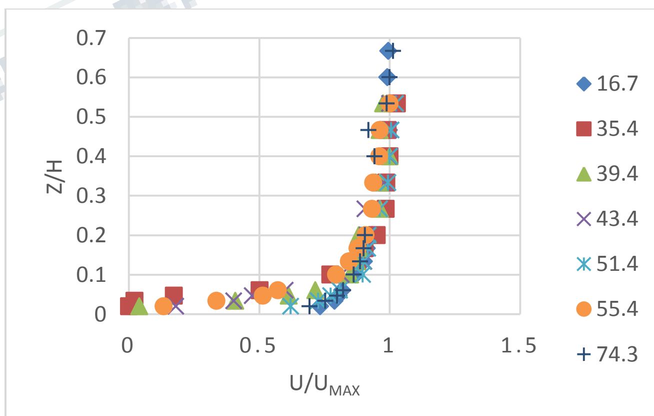

Fig.5 Scaling of streamwise velocity using maximum streamwise velocity($\frac{u}{u_{max}}$) and flow depth ($\frac{z}{h}$)

From above figure shows the plot of ($\frac{z}{h}$)against ($\frac{u}{u_{max}}$)with data collected at different streamwise points inside the patch along the lateral of the cross-section.The range of m-values and the high degree of scattering imply either or both of the

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selected velocity and length scales are appropriate. So by this figure(5) length scale is suitable for scaling.

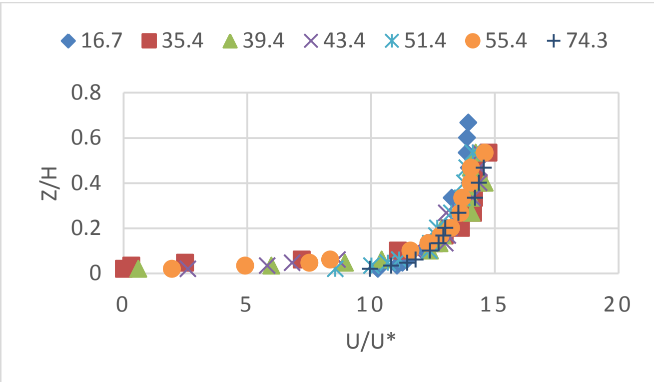

Fig.6:Scaling of streamwise velocity using shear velocity($\frac{u}{u_*}$)and flow depth ($\frac{z}{h}$).

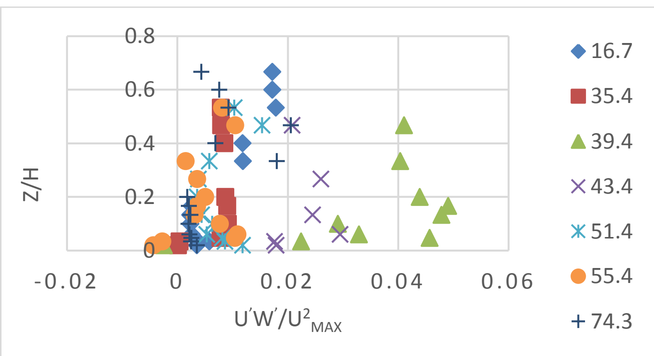

Fig.7Scaling of Reynolds shear stress using($\frac{u\prime w\prime}{u_{max}^2}$) and flow depth($\frac{z}{h}$)

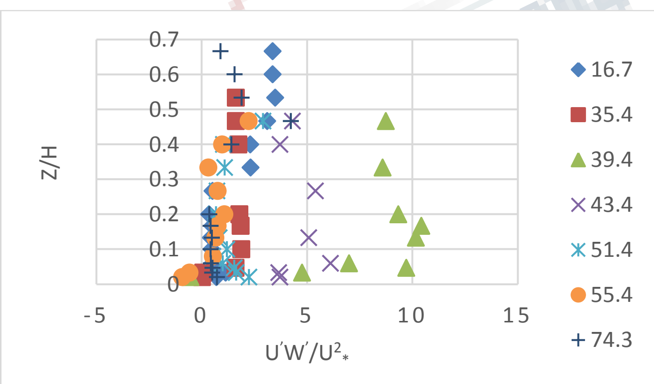

Fig.8Scaling of Reynolds shear stress using ($\frac{u\prime w\prime}{u_*^2}$)and flow depth ($\frac{z}{h}$)

From figures 7 and 8 plots of z/h against Reynolds shear stress ($u'w'$) scaled using $\frac{u\prime w\prime}{u_{max}^2}$ and $\frac{u\prime w\prime}{u_*^2}$, repectively, are shown. It is clear that the scales are inappropriate as obtained profiles are not unique. Whether it is possible to apply the velocity-defect law to relate $\frac{u_{max}-u}{u_*}$to $\frac{z}{h}$is also considered. The figure 14 gives the plot, showing that the relationship is fine suitable.

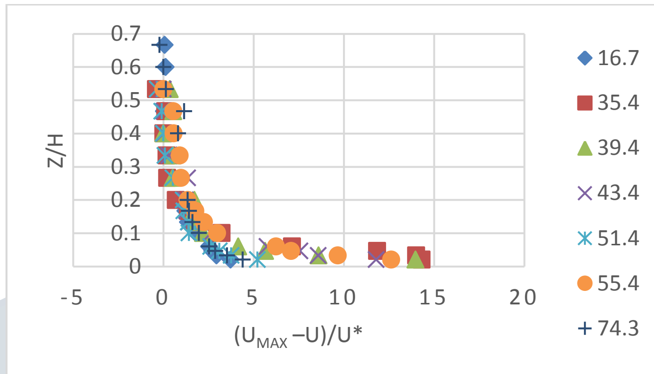

Fig. Scaling of velocity-defect profiles using shear velocity ($\frac{u_{max}-u}{u_*}$) and flow depth ($\frac{z}{h}$)

CONCLUSION

The presence of emergent vegetation and roughness over the channel bed obstructs the open channel flow. The laboratory experiments were done with emergent, sparse and rigid vegetation. Data were collected at different points inside the patch along the lateral cross section.

In this study, the flow depth is taken as the length scale. Maximum streamwise velocity and shear velocity, both are used as velocity scale. Scaling of streamwise velocity, velocity fluctuations along x, y and z directions and Reynolds shear stress is done with both u_{max} and u_* as velocity scales to normalize the profiles. Above scaling for velocity fluctuation are not given desired normalized profiles and thus other scales are to be derived in further work.

Velocity defect law is also scaled using shear velocity is giving a fine suitable plot.

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