ROUGHNESS COEFFICIENTS IN OPEN CHANNEL FLOWS WITH SUBMERGED RIGID VEGETATION

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ABSTRACT

This paper investigates the roughness coefficients in open channels with submerged rigid vegetation. In this study a series of laboratory experiments were undertaken at NIT, Rourkela to investigate the effect of submerged vegetation on flow resistance. The vegetation consisted of rigid rods replicating stem of a tree. Velocities were measured in 3-D Acoustic Doppler Velocimeter with both downward facing and upward facing probes. Vegetations have higher roughness value due to surface drag to resist the flow which decreases the conveyance capacity. The total flow depth in the channel is divided in to two different zones such as vegetation zone and non-vegetation zone or surface layer. The results showed that the longitudinal velocities decreased within and near the vegetation zones and the flow increased towards the non-vegetated zones. Also, the velocity fluctuations and Reynolds stresses are observed to have higher values in the transitions zones between vegetated and non-vegetated zone or near the top of the vegetation in open channels. New expression for predicting roughness coefficients in open channel flows with submerged rigid vegetation has been attempted.

Keywords: Open channel flow, Submerged vegetation, Roughness coefficients, Reynolds Stress, Vegetation density

1. INTRODUCTION

Natural vegetations, such as grasses, shrubs and mangroves frequently grow in main channels, floodplains and wetland water areas. Moreover, vegetation in rivers and coastal zones are important for the control of ecosystems, as well as transport process of sediments. In natural environments, flows are generally over vegetated beds. Vegetations can be submerged or emerged which depend on the depth of flow. Submerged vegetation is defined as the flow of water above the height of stem or vegetation. Hence, the vegetation in channels causes the rise in water elevation even further during high flood discharges. So, it is important to estimate accurately the impact of vegetation on the carrying discharge of a vegetation channel. In rivers, vegetation is an essential part of the ecosystem in restoration. However, from hydraulic point of view, vegetation causes the flow resistance and increases the risk of flooding (Dorcheh, 2007).

The vegetation includes submerged and emerged vegetation, which considerably affects the hydrodynamics, sediment deposition, riverbed evolvement, nutrients and pollution transportation (Nepf and Vivoni, 2000 and Yen, 2002). Huai et al. (2009) investigated on the longitudinal velocity distribution in an open channel flow with submerged rigid vegetation. Also they manifested three hydrodynamic layers from the results of velocity profiles (i.e. the upper non-vegetated layer, the outer and bottom layer within vegetation).

The objective of this present paper extends the study of submerged vegetation i.e., effect of flow resistance and turbulence characteristics vary with different flow depths. Individual relationships are developed between Manning's coefficient (n), friction factor (f), Reynolds number of stem diameter (Re_d), Reynolds number of flow depth (Re_h) and Froude number (Fr) as independent non-dimensional parameters against velocity component U/U^* as non-dimensional dependent parameter respectively. The Reynolds stress components i.e., $\overline{u'v'}$, $\overline{u'w'}$ and $\overline{v'w'}$ have been analyzed for different flow depths along the vertical and lateral directions.

2. THEORETICAL ANALYSIS

For model development of predicting roughness coefficient of a channel with submerged vegetation, different non-dimensional influencing parameters are considered. These have been selected on the basis of Stone and Shen (2002). Those parameters are discussed briefly below:

2.1 Manning's *n* formula

The most commonly used equation for flow resistance in open channel flow computation is the Manning's equation defined as:

$$n = \frac{1}{U} R^{2/3} S^{1/2} \tag{1}$$

where n is Manning's roughness coefficient, R is the hydraulic radius (m) ($R=A/P$, where A is the cross sectional flow area in m^2 and P is the wetted perimeter in m), S is longitudinal bed slope.

2.2 Darcy-Weisbach Formula

According to Chow (1959) the area mean flow velocity can also be calculated by using Darcy-Weisbach formula:

$$U = \sqrt{\frac{8gRS}{f}} \tag{2}$$

where U is mean velocity, f is the Darcy-Weisbach friction factor, g is the acceleration due to gravity (m/s^2).

2.3 Vegetation Density

The number and spacing between the rods are based upon the vegetation density (λ). Non dimensional vegetation density is the product of number of vegetation and area of each stem/rod.

$$\text{Density}, \lambda(\%) = \frac{N\pi D^2}{4} \tag{3}$$

where D is rod/stem diameter (m), N is total number of vegetation per unit area (m^{-2}).

2.4 Reynolds Number

Two different Reynolds numbers has been used for this study i.e., Reynolds number with respect to diameter of stem (Re_d) and Reynolds number with respect to flow depth (Re_h).

Mathematically:

$$Re_d = \frac{UD}{\vartheta} \text{ and } Re_h = \frac{Uh}{\vartheta} \tag{4}$$

Where h is depth of flow (m), ϑ is kinematic viscosity (m^2/s).

2.5 Froude Number

Froude number for each flow depth is defined as:

$$Fr = \frac{U}{\sqrt{gh}} \tag{5}$$

3. EXPERIMENTAL SETUP AND PROCEDURES

Experiments were conducted in a recirculating rectangular tilting flume of length 12m, 0.6m width and a maximum depth of 0.6m with longitudinal slope 0.001 at Hydraulic Engineering laboratory of NIT, Rourkela. The tilting flume is made of mild steel frame with glass wall at the test reach section. The layout of the experimental setup used in the present study is shown in Figure 1.

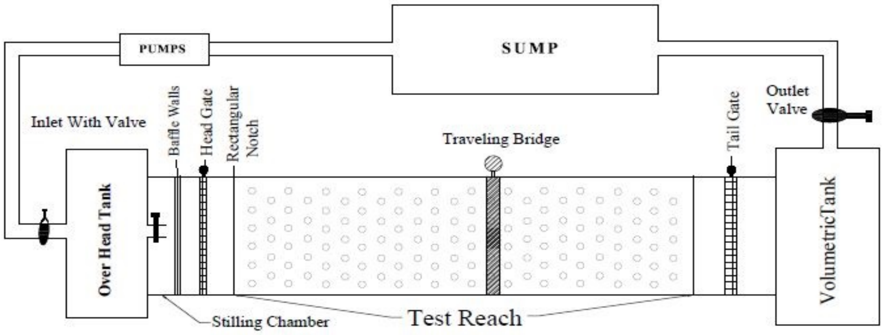

Figure 1: Layout of experimental setup, NITR

In the present study, cylindrical iron rods of diameter 0.0065m are used as replica of vegetation (tree) stems. The rods are drilled into the plywood and filled the holes with adhesives to make it water tight for which water will not seepage through the holes. The staggered pattern of rods with spacing in each row and column was 10cm. The staggered arrangement of vegetation and arrangement of rigid rods in experimental flume are shown in Figure 2 and Figure 3 respectively.

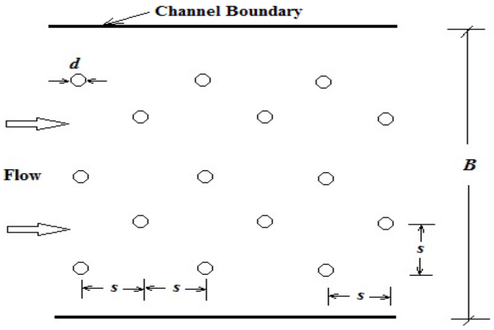

Figure 2: Staggered arrangement of vegetation for experimentation

Figure 3: Arrangement of rigid rods as vegetation in experimental flume

In this study, the important parameters were measured in experimentation i.e., bed slope, depth of flow, velocity and discharge. To measure the bed slope of the channel, the water is to be ponded by closing the tail gate. Local velocities were measured by using three-dimensional 16 MHz micro ADV (Acoustic Doppler Velocimeter) at a number of locations along and across the pre defined channel sections. The discharge are thus computed for every experimental run through time rise method.

4. RESULTS AND DISCUSSIONS

Open channel flow with submerged cylindrical roughness can be visualized as two interacting flow layers. The lower layer containing the cylindrical stems will be referred as the roughness layer or the stem layer. The upper layer i.e., surface layer lies above the stem layer and contains no part of the roughness. Schematic diagram of velocity profile in submerged case is shown in Figure 4.

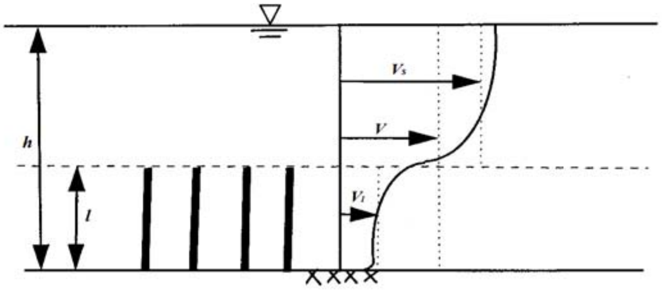

Figure 4: Schematic diagram of velocity profile in rigid submerged vegetation case (Stone and Shen, 2002)

Velocity at different longitudinal distances along the flow direction were measured by ADV and Pitot tube (i.e., where ADV is not accessible) for each experimental run in the rigid vegetated open channel under submerged case. Velocities were measured at every 0.1 *h* intervals where *h* is the flow depth. These measured values of velocities were plotted as velocity profiles and is shown in Figure 5.

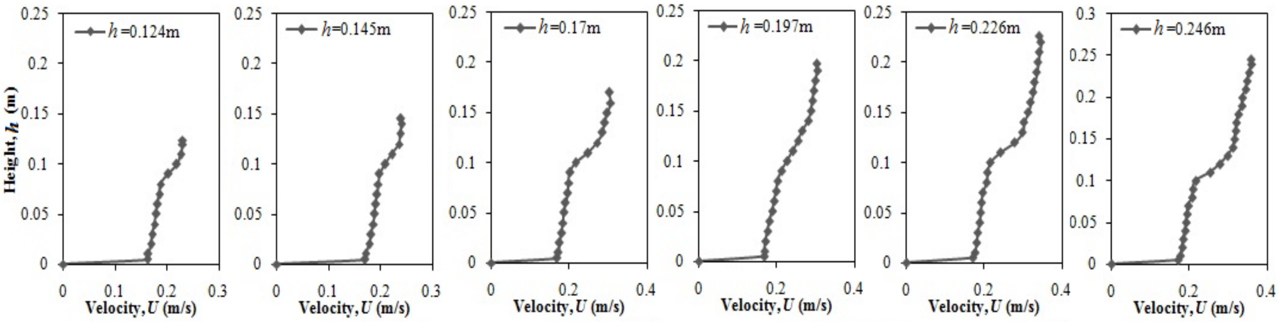

Figure 5: Longitudinal velocity profiles of different flow depths (NITR series)

For non-dimension quantity of velocity term, the longitudinal velocity (U) is normalized by the shear velocity (U^*). The shear velocity id defined as

$$U^* = \sqrt{ghS} \tag{8}$$

The relationships of U/U^* against n, f, Re_d, Re_h and Fr of NITR series data for submerged case are shown in Figure 6.

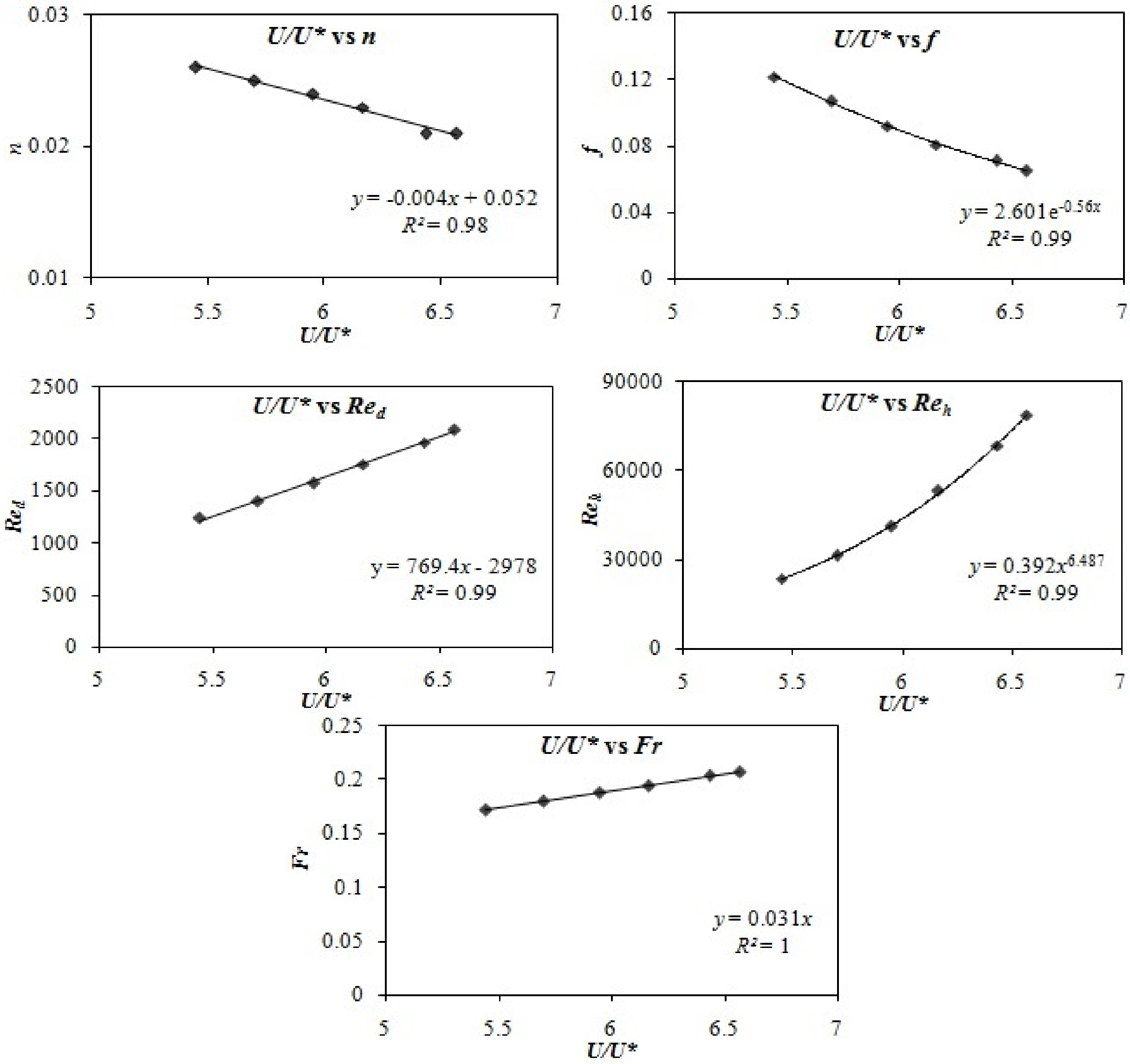

Figure 6: Plot between U/U^* and influencing parameters of NITR series (a) U/U^* vs n (b) U/U^* vs f (c) U/U^* vs Re_d (d) U/U^* vs Re_h (e) U/U^* vs Fr

The relationships between U/U^* with n, f, Re_d, Re_h and Fr are presented from equation 9 to 13 respectively.

The relationship between U/U^* and n

$$n = -0.004\frac{U}{U^*} + 0.052,\ \mathrm{R}^2{=}0.98 \tag{9}$$

The relationship between U/U^* and f

$$f = 2.601e^{-0.56\frac{U}{U^*}},\ \mathrm{R}^2{=}0.99 \tag{10}$$

The relationship between U/U^* and Re_d

$$\mathrm{Re}_d = 769.4\frac{U}{U^*} - 2978 \text{, } R^2=0.99 \tag{11}$$

The relationship between U/U^* and Re_h

$$\mathrm{Re}_h = 0.392\frac{U}{U^*}^{6.487} \text{, } R^2=0.99 \tag{12}$$

The relationship between U/U^* and Fr

$$Fr = 0.031\frac{U}{U^*} \text{, } R^2=1 \tag{13}$$

The From Figure 6 it has been observed that U/U^* increased with increase in Reynolds number of stem diameter (Re_d), Reynolds number of flow depth (Re_h) and Froude number (Fr) respectively. But U/U^* is decreased with increase in Manning's roughness coefficient (n) and friction factor (f) respectively.

7. CONCLUSIONS

The various roughness coefficients and other influencing parameters are discussed and also the variation of Reynolds stress along the flow depth and lateral directions are analyzed in this present study with submeregd vegetation.

The following conclusions are derived from the present study:

1. The relationships between n, f, Re_d, Re_h and Fr against U/U^* are presented.
2. Under fully submerged conditions, the flow is highly sheared near top of the rods. The longitudinal velocities closely follow the same logarithmic profile. It is also observed that a transition in velocity occurs between vegetation layer and free surface layer. Just below the top of the rods, the velocity data diverges from a logarithmic profile.
3. Additional research is desirable to validate the applicability of the rigid vegetation model developed in this study to flexible vegetation conditions and rigid vegetation with different set of vegetation density.

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