FLOW RESISTANCE IN OPEN CHANNEL WITH EMERGENT RIGID VEGETATION

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ABSTRACT

This paper presents the flow resistance in open channel flow with emergent rigid vegetation. Vegetation can be actively used as flood management resistance tool, enhance the sustainability and restoration of the ecosystem. Irregular growth of vegetation in channels increases the hydraulic resistance which leads to energy loss and conveyance capacity which can be problematic. The flow resistance produced by uniformly distributed vegetation stems has been thoroughly investigated from the previous experimentations. The vegetation consists of rigid rods replicating stem of a tree. Velocities were measured using 3-D Acoustic Doppler Velocimeters (ADV), with both downward facing and upward facing probes. It has been observed that behind the vegetation stem, the magnitude of the longitudinal velocities became very less. However, the other two velocities i.e., transverse and vertical velocity were high due to occurrence of turbulence. The results show that flow resistance varies with flow depth, vegetation length, stem diameter and vegetation density. Also it has been observed that the flow rate decreased with increase in vegetation density. Experimental data sets of NITR and past researchers have been taken for developing a new mathematical relationship for roughness in terms of non dimensional parameters. The mathematical expression has been proved to match well with the experimental data sets and found to be better as compared to that of the conventional equations.

Keywords: Open channel, Flow resistance, Friction factor, Manning's coefficient, Rigid vegetation

1. INTRODUCTION

Vegetations, such as grasses, shrubs and mangroves frequently grow in main channels, floodplains and wetland water areas. They increase the hydraulic resistance to water flow and reduce the shear stress at the bed of the channel. Thus, the flow carrying capacity of the open channel will be reduced. Also, the potential of confining and deposition of sediments will be improved. Moreover, vegetation in rivers and coastal zones are important for the control of ecosystems, as well as transport process of sediments. In rivers, vegetation is an essential part of the ecosystem in restoration. Restoration must have multifunctional considerations whether these are ecological, morphological, hydrological and water quality (Brookes and Shields, 1996). The hydraulics of natural rivers is complex and strenuous to interpret. However, from hydraulic point of view, vegetation causes the flow resistance and decrease the risk of flooding. Vegetations can be submerged or emergent which depend on the depth of flow. Emergent vegetation is defined as the flow of water up to some height of stem and some portion extends out of the water.

Vegetation also reduces erosion by absorbing the impact of rain drops (i.e. reducing dislodging), reducing the velocity of runoff (i.e. reducing the flux), binding soil with roots and protecting soil from wind and sun effects (i.e. preventing drying) (Goldman and Jackson, 1986). Tsujimoto et al. (1991) investigated the mean flow and turbulence characteristics for rigid and flexible vegetation. The type of vegetations obstruct to the flow, which enhance the friction by generating "complex two dimensional currents, eddies and stagnation regions, as well as vegetation scale turbulence" (Furukawa et al., 1997). Meijer and Van Velzen (1998) used steel rods as well as natural reeds for their experiments. Nepf (1999) developed and tested a physical model which predicts the turbulence intensity, vegetation drag and diffusion within emergent vegetation. Stone and Shen (2002) studied the hydraulic resistance of flow and modelled with cylindrical stems under emergent and submerged conditions. Ghisalberti and Nepf (2002) used a simple model of eelgrass meadow.

The objective of this present paper extends the study of emergent vegetation i.e., effect of flow resistance and drag coefficient varies with different flow depth and vegetation density. A mathematical model is developed with relationship between friction factor (f), Manning's coefficient (n), Reynolds number (Re) and vegetation density (λ) as independent non dimensional parameter and drag coefficient (C_D) as dependent parameter. The variation of C_D against D/s, Re_d, Re_h, Fr and λ has been analyzed for model development.

2. THEORETICAL ANALYSIS

For model development of drag coefficient, different non-dimensional influencing independent parameters are to be considered. Those parameters are discussed 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:

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

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

2.2 Darcy-Weisbach Formula

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

$$U = \sqrt{\frac{8gRS}{f}} \tag{3}$$

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

The relation between Darcy-Weisbach friction factor and Manning's n can be expressed as:

$$f = \frac{8gn^2}{R^{1/3}} \tag{4}$$

2.3 Drag Coefficient

The drag force (F_D) per fluid mass due to vegetation can be formulated as (Thom, 1975)

$$F_D = \frac{1}{2} \rho A C_D U^2 \tag{5}$$

where ρ is the density of water, U is the mean velocity of uniform flow, A projected area to the flow and C_D is drag coefficient.

2.4 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.

$$\text{Density}, \lambda(\%) = \frac{N\pi D^2}{4} \tag{6}$$

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

2.5 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:

$$\text{Re}_d = \frac{UD}{\nu} \quad \text{and} \quad \text{Re}_h = \frac{Uh}{\nu} \tag{7}$$

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

2.6 Froude Number

Froude number for each flow depth is defined as:

$$Fr = \frac{U}{\sqrt{gh}} \tag{8}$$

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.

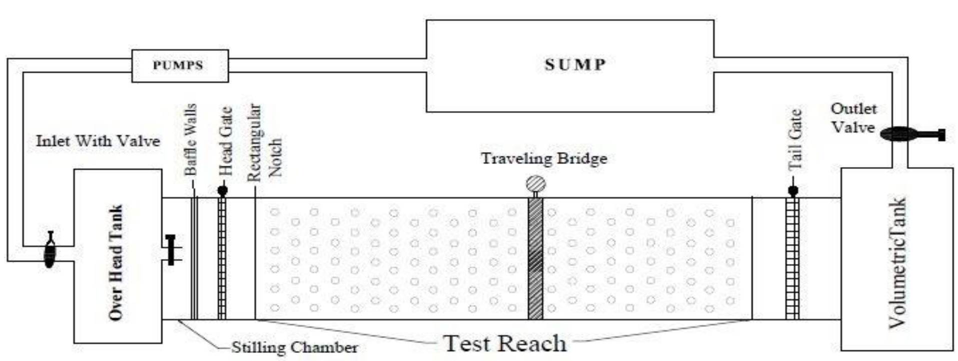

Figure 1: Layout of experimental setup, NITR

In the present study, cylindrical iron rods of diameter 6.5mm 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.

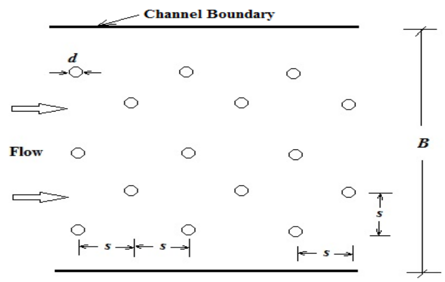

Figure 2: Staggered arrangement of vegetation for experimentation

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.

4. LONGITUDINAL VELOCITY PROFILES

An emergent condition can be considered as limiting condition of a submerged condition with no surface layer. Velocity profiles are followed the log law profile. The effect of bed friction on the shape of the profile is important only very near the bed surface where the profile decreases to zero (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 emergent cases. 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 4.

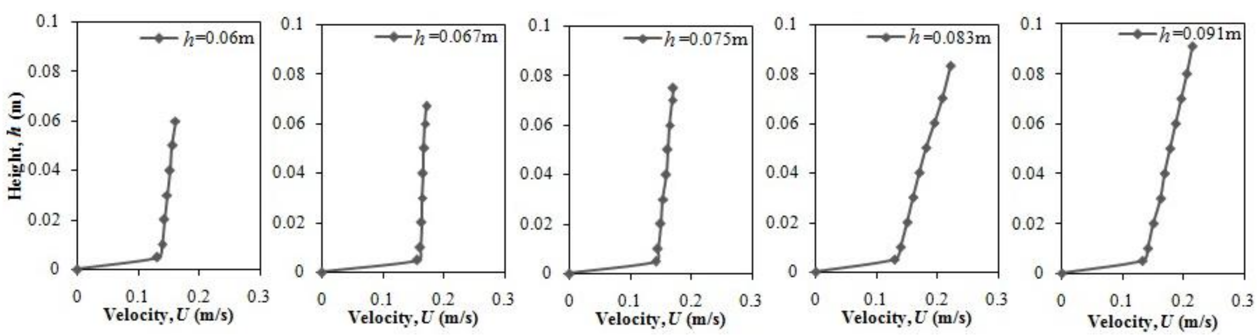

Figure 4: Longitudinal velocity profiles of different flow depths (NITR series)

4. MODEL DEVELOPMENT

Drag coefficient (C_D) is an important study for every experimental study with vegetation. So, this paper tries to develop a multi-variable regression model by taking some important non-dimensional parameters so that it will help to find out the drag coefficient. For this present model C_D is taken as dependent parameter and D/s, Re_d, Re_h, Fr and λ are taken as independent parameters. The variation of C_D against D/s, Re_d, Re_h, Fr and λ has been analyzed for model development.

Finally, using the data of the best fit models of different parameters and the model has been developed for drag coefficient. A multi-variable regression model has been developed as:

$$C_D = 3.375 + 0.217 \, {D/s}^{0.063} + 2.35 \mathrm{Re}_d^{-0.03} + 0.998 \mathrm{Re}_h^{-0.03} - 2.339 Fr^{-0.03} - 2.709 e^{-0.01\lambda} \qquad (8)$$

5. CONCLUSION

Flow resistance is the most important hydraulic parameter of vegetated open channel flow. The various flow resistances like vegetal drag coefficient (C_D), Manning's roughness coefficient (n), and Darcy-Weisbach friction factor (f) are found to be more for vegetated open channel. The dependence of the drag coefficient on Re_d, Re_h, Fr, D/s and λ is analyzed in this present study with emerget vegetation case.

The following conclusions are derived from the present study:

1. Regression based multi-variable model has been developed to predict the drag coefficient relating to Reynolds number of stem diameter, Reynolds number of stem height, Froude's number, Manning's *n* and vegetation density under emergent rigid vegetation conditions.
2. Additional research is desirable to validate the applicability of the rigid vegetation model developed in this study to flexible vegetation conditions.

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