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Effects of Land Slope and Flow Depth on Retarding Flow in Non-submerge Vegetated Lands

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Abstract: To evaluate effects of flow rate and flow depth on friction factor, tree models of pine and cedar were subjected to a series of flow rates at different flow depths. To include effects of land slope on the analyses in this study, boundary shear approach (instead of direct drag force measurement) and dimensional similitude were used to develop a relation between flow velocity and land slope. Results showed that friction factor was considerably decreased, thus flow was less retarded with increase of land slope as a result of increase in flow velocity and streamlining of the vegetation. Also, friction factor increased with increase of flow depth due to submergence of more rough elements with flow depth.

Key words: Flow retardation, vegetation, irrigation, land conservation

INTRODUCTION

Vegetation in farms, ranges and watersheds produces high resistance to flow and as a result has a large impact on flow retardation, water penetration, sedimentation and erosion. For these reasons, the estimation of vegetation resistance to flow and friction factors is an important aspect of work dealing with irrigation, drainage and land conservation. In open channel flow the most common friction factors include Darcy-weisbach friction factor (f) and Manning coefficient (n) which can be easily converted to each other through common channel flow equations.

For more than a century many empirical and quasi-theoretical equations have been derived for the estimation of vegetation roughness in river beds and banks. Despite having the same principal, little is known on how to apply this principal to formulate surface runoff and flow retardation in crop and grass land as well as in vegetated watersheds. The main reason could be that river flow and vegetated roughness equations are primarily based on the channel velocity of flow which is not easily estimated for farms and open lands. Non-canalized flow in open lands is normally expressed by slope rather than velocity.

Flow resistance of submerged and non-submerged vegetation: The flow resistance problem can be classified in two different categories: flow over short submerged vegetation and flow through tall non-submerged vegetation. Theory of resistance to flow in submerged vegetation is completely different from that in non-

submerged vegetation. The governing equations for the submerged condition are based on the relative roughness and theory of boundary layer above the vegetation. For the submerged condition, many experiments have been conducted by the US Department of Agriculture to estimate vegetation roughness in small channels and crop furrows. Result of the work was the construction of a series of n - VR curves to relate Manning roughness coefficient (n) to velocity (V) and hydraulic radius (R) for submerged crops (USDA, 1954). Stephan and Gutknecht (2002) and Jarvela (2003) used the log velocity profile of turbulent boundary layer flow to develop an approach to estimate the roughness for flow over submerged and flexible vegetation. Fathi-Moghadam and Sharify (2005) used same principal to estimate effects of depth and land slope on friction factor for submerged grass lands. The most important component of the analysis was the inclusion of a vegetative stiffness number that allowed the effects of bending and streamlining of the vegetation to be reflected in the friction factor. They found that the friction factor (f) decreases with increase of the flow depth due to decrease of relative roughness. The friction factor also decreased with increase of land slope as result of flow velocity increase and streamlining of vegetation.

In non-submerged vegetation, according to Einstein and Banks (1950), the total resistance due to an array of submerged roughness elements that exhibit primarily profile drag characteristics may be based upon the drag coefficient value for an individual element and the additive property among separate roughness contributions. For non-submerged vegetation, based on

extensive field measurements, the US Department of Agriculture published a list of friction factors for different row crops and small slope vegetated waterways where the effect of vegetation deformation was negligible (Ree and Crow, 1977). Petryk and Bosmajian (1975) based their analysis of resistance to flow through vegetation on the additive property although their analysis did not include deformation of the plants due to a flow. This additive property was found to hold for a set of single and multiple cedar and pine tree models placed with different patterns and densities in a flume (Fathi-Moghadam and Kouwen, 1997).

The purpose of this study is to estimate effects of land slope and flow depths as the main parameters to balance run away and retardation of water for non-canalized flow in farms and non-submerged vegetated lands. Since data for method of Fathi-moghadam (1996) was available, this method for non-submerged vegetation was used in this study. Details of the method can be found in Fathi-Moghadam and Kouwen (1997). The method was improved in Kouwen and Fathi (2000) for application in river flow models and a table to estimate Manning's coefficient at any flow velocity was also presented. Advantages of the method over existing methods for estimating resistance factors is its ability to account for the interaction between vegetation and flow, taking into account velocity, depth of flow and vegetative conditions (including type, size, stage of maturity and density of vegetation). More recent studies of resistance to flow in non-submerged vegetation by Stone and Shen (2002) and Jarvela (2002, 2004) used the same principal as in Fathi-Moghadam and Kouwen (1997), but are less advantageous in practice.

Based on boundary shear relation and dimensional analysis a relation was developed for substitution of flow velocity with land slope in the analysis. Hence effects of flow depth and land slope on friction factor and flow retardation were estimated.

MATERIALS AND METHODS

Fathi-Moghadam (1996) conducted flume tests at the Fluid Mechanic Laboratory of the University of Waterloo, Canada. The mean velocity (V), drag force (F_D), momentum absorbing area (A , one side of the foliage area for the model trees) and the bed area covered (a) by the model trees were measured for a range of flow depths in a constant slope of 0.004. The experiments were repeated in a 0.5×0.5×11 m flume for single cedar and pine tree models and the tree models were grouped in various arrays. These flume tests indicated that the drag force of

models (0.3 m in length) placed in various arrays are additive. Based on the additive property, dimensional analysis and experimental results, a mathematical model was correlated for estimation of the friction factor for flow through non-submerged vegetation zones of waterways. The final form of the mathematical model is (Fathi-Moghadam and Kouwen, 1997; Kouwen and Fathi, 2000):

$$f = 4.06 \left(\frac{V}{\sqrt{\frac{\xi E}{\rho}}} \right)^{-0.46} \left(\frac{y_n}{h} \right) \quad \text{for } y_n \leq h \quad (1)$$

The flow properties are represented by the average channel velocity (V), the density of fluid (ρ) and the normal flow depth (y_n). The vegetative properties are represented by the average plant height (h) and the vegetation index (ξE), which is unique for all specimens of a plant species. This index is obtained from the resonant frequency, mass and length of a plant species and a mathematical model developed by Fathi-Moghadam (1996). The index reflects shape and mechanical behavior of a plant species as a result of increasing flow velocity.

Formulation for Friction Factor (f): The Darcy-Weisbach friction factor (f) is theoretically defined in fluid mechanics textbooks as:

$$f = 8 \left(\frac{V_*^2}{V^2} \right) \quad (2)$$

where V_* is shear velocity and V is mean channel stream velocity. Using a force equilibrium equation for uniform flow in the flow-wise direction of a wide vegetated reach, the average boundary shear stress (τ_o) can be expressed as:

$$\tau_o = \frac{F_D}{a} = \frac{1}{2} C_d \left(\frac{A}{a} \right) \rho V^2 \quad (3)$$

where F_D is drag force absorbed by vegetation, a is the bed horizontal area covered by the vegetation, C_d is drag coefficient, A is Momentum Absorbing Area (MAA) and is closely related to the one-side area of leaves and stems and ρ is mass density of water. Since by definition, $\tau_o = \rho V_*^2$ the friction factor (f) will be:

$$f = 4C_d \left(\frac{A}{a} \right) \quad (4)$$

The ratio A/a is a direct indicator of the biomass per unit area and is commonly referred to as the Leaf Area Index (LAI). Jarvela (2002, 2004) reanalyzed LAI data measured by Fathi-Moghadam (1996) to determine mechanical properties of plant species. Jarvela (2004) developed his method based on Fathi-Moghadam (1996) assumption for uniform distribution of LAI over the height of vegetation. LAI can be measured by ground-based equipment in the field or by using remote sensing techniques. The increased availability of high resolution satellite data makes the analysis of large vegetated area possible (Rautiainen *et al.*, 2003; Stenberg *et al.*, 2003).

Combining Eq. 3 and 4, friction factor (f) is calculated from (Fathi-Moghadam and Kouwen, 1997):

$$f = \frac{8F_D}{\rho V^2} \quad (5)$$

where F_D is the fluid drag force on model trees as measured by load cells. A micro-propeller was used to measure the mean channel stream velocity (V).

RESULTS AND DISCUSSION

Variation of correlated friction factor (f , estimated from equation 1) for four relative depths of submergence ($y_n/h = 0.2, 0.45, 0.7$ and 1.0) and four flow velocities ($V = 0.1, 0.2, 0.3$ and 0.5 m sec^{-1}) to are shown in Fig. 1 for flow through pine and cedar tree models. To avoid complication, correlated friction factors for cedar and pine were averaged and their velocity curves denoted by V_f in the figure. Friction factors reported by Jarvala (2002) for the same range of flow velocity through dense willows are also shown in the figure. Figure 1 shows similar variation of friction factor with flow depth and flow velocity for both the model of Fathi-Moghadam (1996) and the reported friction factors by Jarvela (2002). This validates application of the model by Fathi-Moghadam (1996) Fathi-Moghadam and Kouwen (1997), Kouwen and Fathi (2000) in this study. The difference in absolute values of friction factors is primarily due to differences in vegetation type and density.

In contrast with the flow velocity, the land slope is a geometric parameter that is more suitable and easy to measure for non-canalized flow of open lands. In this study, to include effects of land slope on the analysis for estimation of friction factor and surface flow retardation for non-submerged vegetation, the well known boundary shear equation:

$$\tau_o = \gamma y_n S \quad (6)$$

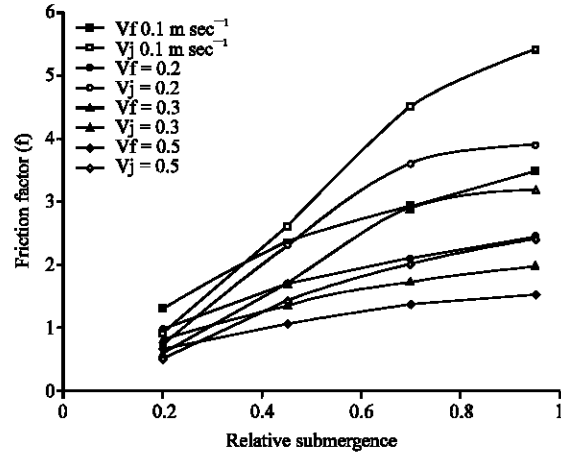


Fig. 1: Variation of friction factor (f) with flow depth and flow velocity: (a) Velocity curves denoted by V_f are Fathi-Moghadam data, averaged for pine and cedar tree models, (b) V_j curves are extracted from Jarvela (2002) data for willows

was used to calculate τ_o , then F_D in equation 5. γ is water specific weight. By this way, land slope represents drag force in Eq. 5 and direct measurement of drag force is not required for the calculation of friction factor as was measured by Fathi-Moghadam (1996) for development of Eq. 1.

Based on dimensional similitude and use of Eq. 5 and 6, a functional relationship between velocity of flow and land slope for the related friction factor (f) and flow depth (y_n) is developed as:

$$\frac{S_1}{V_1^2} = \frac{S_2}{V_2^2} \quad (7)$$

Equation 7, can be used to covert the flow velocity data to the related land slope data where a reference land slope (S_1) and flow velocity (V_1) are available. This allows the replacement of velocity (V) in Eq. 1 by land slope (S). Equation 7 can be derived from any relation of drag coefficient i.e., the drag coefficient developed by Stone and Shen (2002).

In a rational method, Eq. 7 can also be directly used to convert equal velocity curves in Fig. 1 to equal slope curves for estimation of friction factor (f). In this study, reference average velocity (V_1) of 0.98 m sec^{-1} and 0.92 m sec^{-1} for cedar and pine tree models, respectively (recorded at reference slope $S_1 = 0.004$) were used in Eq. 7 to calculate related slopes (S_2) for a range of velocities (V_2) from 0.1 to near 1 m sec^{-1} . The results for variation of friction factor (f) with flow depth and land slope are illustrated in Fig. 2 and 3 for cedar and pine tree

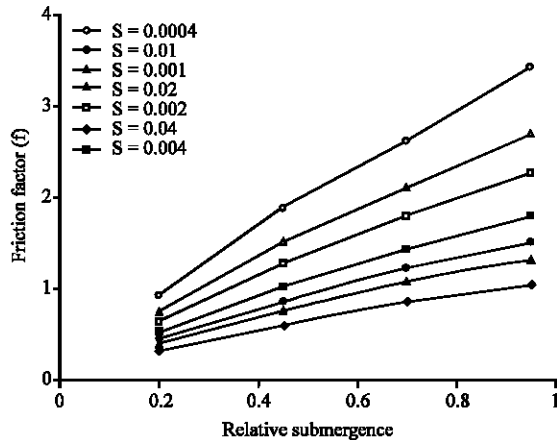


Fig. 2: Variation of friction factor (f) with flow depth and slope for non-submerged cedar tree models

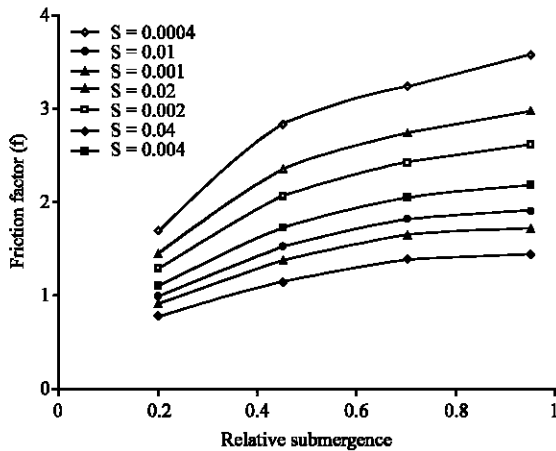


Fig. 3: Variation of friction factor (f) with flow depth and slope for non-submerged pine tree models

models. The figures show that streamlining of the vegetation elements as a result of increase in channel slope and velocity decreases friction factor (f) and the flow retardation. An inverse result was obtained as the flow depth increases in non-submerged vegetation. Friction factor (f) increases as more vegetation elements submerge with increase of flow depth.

CONCLUSIONS

A mathematical model for non-submerged vegetation was used to evaluate effects of flow depth and land slope on the friction factor as a parameter to measure flow retardation for non-canalized flow in farms, ranches and watersheds. The model has previously been developed based on the experimental measurements of flow through

non-submerged pine and cedar tree models (Fathi-Moghadam and Kouwen, 1997). The estimated friction factors by the model were confirmed with the reported friction factors in the literature. The following conclusions were obtained:

- The friction factor (f) or flow retardation is directly proportional to the flow depth for non-submerged conditions.
- The friction factor (f) or flow retardation decreases with increase of land slope and flow velocity as a result of flexibility and streamlining of vegetation.
- Use of average boundary shear Eq. (6) allowed the flow velocity measurements to be replaced by land slope as a geometric parameter that could be measured more easily in non-canalized vegetated lands. Using Eq. 6 in the analysis, direct measurement of drag force is not required. Elimination of direct drag force measurements allows easier development of mathematical models for estimation of friction factor in practice.
- Direct measurements of slopes less than 0.001 contribute large errors in short experimental flumes. Therefore, application of Eq. 7 has the advantage of excluding these errors when higher measured slope and flow velocity are used as reference to calculate lower ranges of slopes and flow velocities.

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