HYDRAULICS OF VEGETATED OPEN-CHANNEL FLOWS

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INTRODUCTION

Close-to-nature river works may provide us with many good points. Vegetation in open-channels reduces the peak discharge by increasing roughness during floods. It also mitigates sediment carrying capacity of the river, and thus improve the turbidity level due to suspended solids. Vegetation brings improvement of habitats for wildlife in the river and of water quality by filtering the pollutants. Vegetation is also known to contribute to bank stability. Recently, however, it seems that advantages of close-to-nature design of the river are too much emphasized without investigating the role of vegetation in the river hydraulically. Thus a better understanding of the flow structure and sediment and solute transport relevant to it is desired.

A backwater equation for vegetated open-channel flows is introduced from the boundary layer theory in the present study. The equation predicts the backwater profile in terms of vegetation density, drag coefficient, and Boussinesq coefficient. Obviously, this presents an improved methodology compared to previous tools, and it will provide more systematic estimations of discharge characteristic of vegetated open-channels. The new routing method can be applied to both rigid and flexible roughnesses. Drag models for both rigid and flexible roughnesses are applied, and impact of vegetation density is investigated for steady uniform and gradually varied flows. The outcomes of this study may help better understanding of the carrying capacity of floodplain the roughness of which is clearly different from that of main channel due to vegetation.

GOVERNING EQUATIONS

For steady, vegetative, open-channel flows, the continuity and momentum equations in the x- and z-directions are given by, respectively,

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad (1)$$

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\frac{\partial \tau}{\partial z} + gS_o - \frac{f_D}{\rho} \qquad (2)$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \qquad (3)$$

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where u and w are velocity components in the x– and z–directions, respectively, p is the pressure, τ is the shear stress due to laminar viscosity and Reynolds stress, S_o is the channel slope, g is the gravitational acceleration, ϱ is the density of water, and f_D is the drag force per unit mass of water. In eq.(2), f_D is given by

$$f_D = \frac{1}{2}\rho c_D a u^2 \tag{4}$$

where c_D is the drag coefficient and a is the vegetation density [L^{-1}]. Integrating eqs.(1)–(3) by introducing the kinematic boundary condition yields the following steady–state backwater equation:

$$\frac{dH}{dx} = \frac{S_o - S_f - S_{fv}}{(1 - \beta Fr^2)} \tag{5}$$

where H = flow depth, $Fr = U/\sqrt{gH}$, U = depth–averaged velocity, β = momentum correction factor, $S_f = \tau_b/(\rho gH)$, τ_b = shear stress at the bottom, and S_{fv} is the slope due to vegetation defined by

$$S_{fv} = \frac{1}{2}\beta \bar{c}_D a Fr^2 H \tag{6}$$

where $\bar{c}_D$ is the bulk drag coefficient which is depth–averaged. A detailed derivation is given in Choi (1997). According to eq.(5), vegetation affects the backwater profile by the friction slope due to the vegetation (the third term) and by the profile constant β.

DRAG COEFFICIENT

Rigid Roughness

Dunn (1996) carried out experiments of open–channel flows with simulated vegetation. He obtained values of $\bar{c}_D$ as 0.26 ± 0.14 for rigid cylinders with Reynolds number ranging between 57,000–258,000. In the experiments, the submergence ratio lies in the range of 0.30–0.71.

Flexible Roughness

For flexible roughnesses, the drag coefficient tends to decrease due to bending of vegetation as the flow velocity increases. There is also an increase in the area of foliage hidden behind the frontal area that also absorbs momentum, but can not be seen by a flow–wise view. For subcritical turbulent vegetated open–channel flows, Fathi–Maghadam and Kouwen (1997) derived the following relationship by dimensional analysis and verified through experiments:

$$\bar{c}_D\left(\frac{A_*}{A_h}\right) = f(U^2) \tag{7}$$

where A_* is the momentum absorbing area which is closely related to the one-sided area of leaves, and A_h is the unit horizontal area covered by vegetation. FIG. 1 shows curves for pine and cedar trees which are regressed from experimental observations by Fathi-Maghadam and Kouwen (1997).

APPLICATIONS

Uniform Flow

Computations are performed with unit discharge of $q = 0.6$ m^2/s in the open-channel, whose slope and roughness coefficient are $S_o = 0.0035$ and $n = 0.015$, respectively. Plants on the channel are assumed to be rigid with drag coefficient of $\bar{c}_D = 0.2$. Computed normal depth and Froude number for vegetation densities are given in FIG. 2. It is seen that the normal depth increases as the vegetation density increases due to the decrease in the channel conveyance. Froude number is observed to decrease accordingly.

In order to compute the normal depth of open-channel flow with flexible roughnesses, such relationship given in FIG. 1 may be used. Sample computations are carried out with an open-channel of previous slope and bottom roughness. FIG. 3 shows the change in normal depth of three different channel conditions when the unit discharge increases from 0 to 1.0 m^2/s. It is seen that the normal depth of the vegetated open-channel is higher than that of the plain channel due to the resistance by vegetation. The normal depth of the channel where the pine tree is planted greater than the one by cedar tree.

Gradually Varied Flow

Backwater calculations are carried out by using eq.(5). A wide rectangular open-channel with the same slope and roughness as before is assumed to convey a unit discharge of $q = 0.6$ m^2/s. M1 type profile is obtained with downstream water depth of 1 m. FIG. 4 shows impact of vegetation density. It is observed that the normal depth increases as the vegetation density increases, which is consistent with the discussion in the uniform flow case. It turns out that thicker density of vegetation in the open-channel decreases flow velocity and reduces the region influenced by backwater.

The relationship in FIG. 1 for the flexible roughness is applied to the gradually varied flow, and the calculation results with a downstream depth of 1.5 m are given in FIG. 5. The unit discharge and the channel slope are the same as the previous examples. The flow resistance by vegetation is observed to increase the water depth, thus converging rapidly to the normal depth in the upstream direction.

CONCLUSIONS

A backwater equation has been derived for vegetative open-channel flows. The new governing equation contains a new slope term in terms of vegetation density, drag coefficient, and Boussinesq coefficient. Drag models for both rigid and flexible cylinders are introduced. Using the new governing equation, computations of uniform flow and gradually varied flow were performed.

References

Choi, S.-U. (1997). "Boundary layer theory for vegetated open-channel flows." *Magazine of Korea Water Resources Association*, 30(6), 62-65 (in Korean).

Dunn, C.J. (1996). "Experimental Determination of Drag Coefficients in an Open-channel with Simulated Vegetation." Master thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, IL.

Fathi-Maghadam, M., and Kouwen, N. (1997). "Nongrid, nonsubmerged, vegetative roughness on floodplains." *Journal of Hydraulic Engineering*, ASCE, 123(3), 51-57.

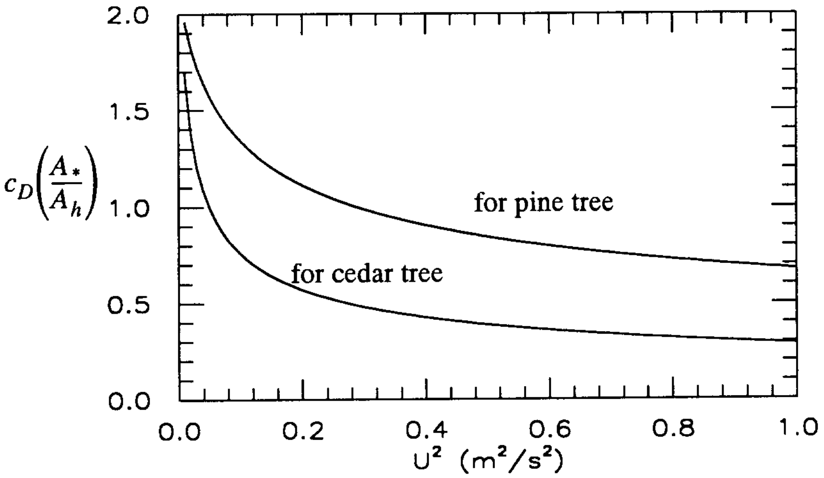

FIG. 1. Roughness Parameter for Flexible Cylinders (Fathi-Maghadam and Kouwen, 1997)

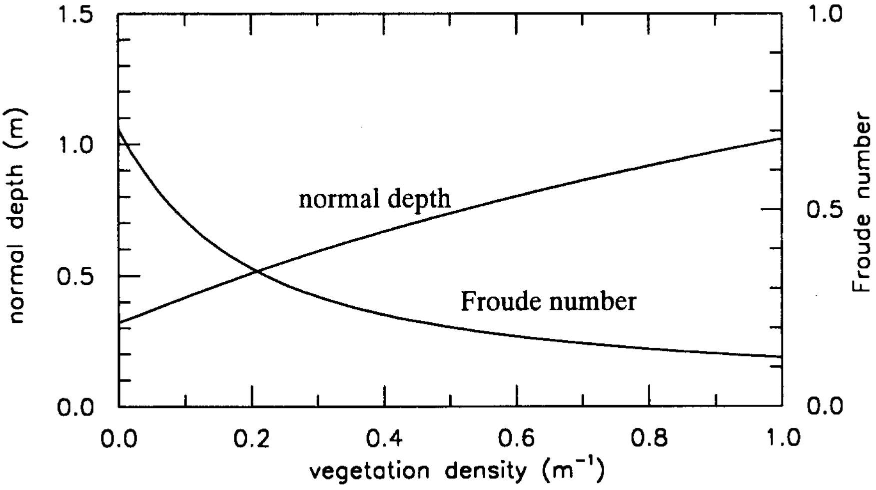

FIG. 2. Impact of Vegetation Density in Uniform Flow

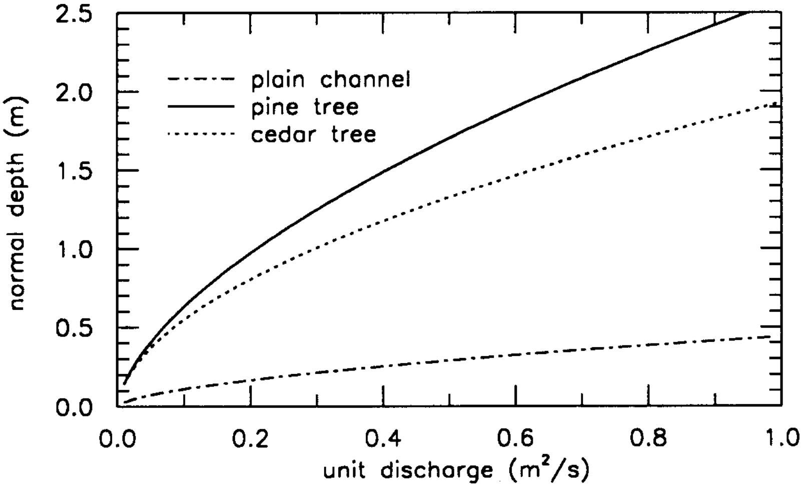

FIG. 3. Normal Depth versus Unit Discharge

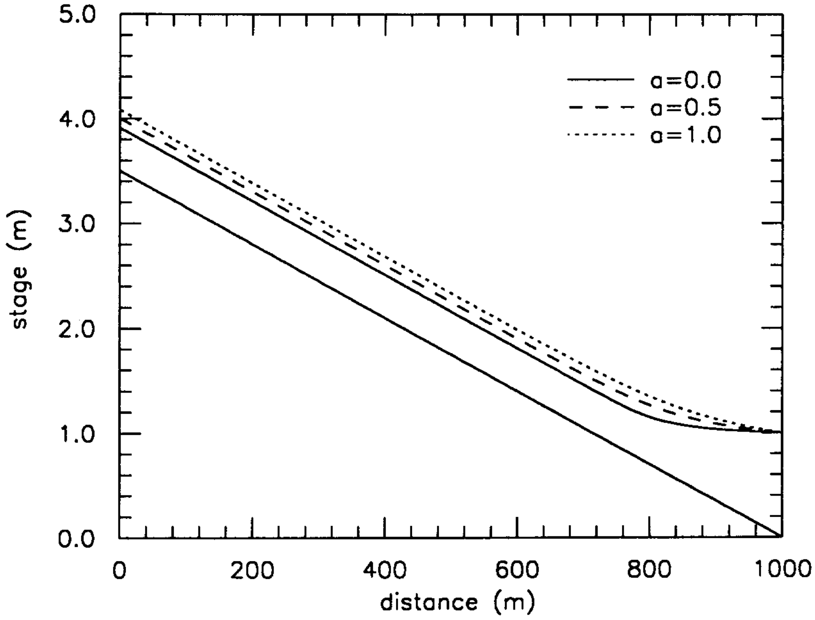

FIG. 4. Impact of Vegetation Density

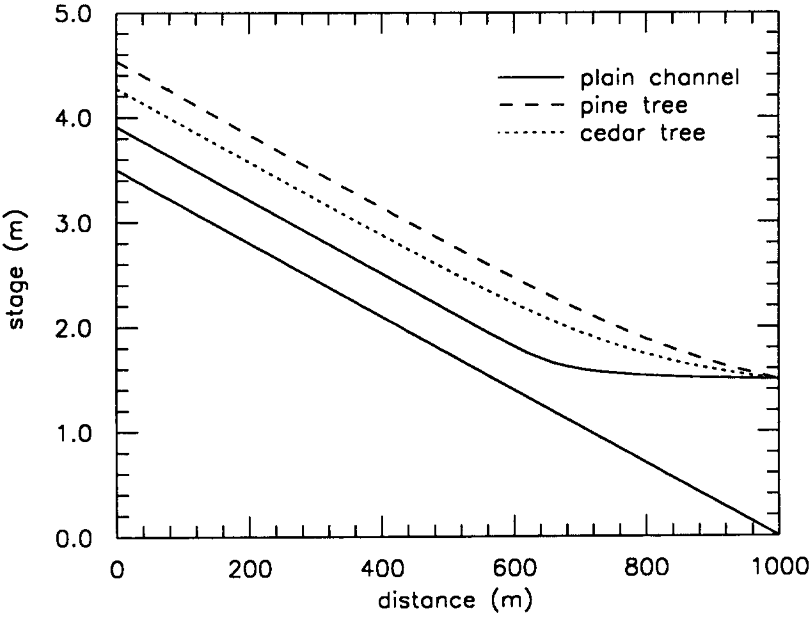

FIG. 5. Backwater Profile by Flexible Roughness