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# TWO-LAYER MODEL FOR OPEN-CHANNEL FLOWS WITH SUBMERGED VEGETATION

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## ABSTRACT

Unlike terrestrial canopy flows and flows with emergent vegetation, depth-limited open-channel flows are characterized by two distinct flow structures in the vegetation and upper layers. In this paper, a two layer model for depth-limited flows with submerged vegetation is described. The model assumes uniform and logarithmic velocity distributions in the vegetation and upper layers, respectively. Relationships for the mean velocity in the vegetation and upper layers are provided. In addition, for this type of flows, the mean velocity formula and the roughness increased by vegetation are proposed. The proposed relationships are applied to the authors' and others' experimental data, showing a good performance.

*Keywords*: two-layer model, open-channel flows, submerged vegetation

## 1. INTRODUCTION

The efficiency of river rehabilitation in aquatic system is seldom free of vegetative influence. That is, to improve the living conditions and habitat heterogeneity, vegetation is widely used to increase the habitat suitability index (HSI) which is described by the flow depth and the flow velocity, and morphology (Newson and Newson, 2000; Wheaton et al., 2004; Schneider, 2004). Furthermore, submerged vegetation plays an important role in the chemistry and biology of aquatic systems. Vegetation can improve dramatically water quality by direct uptake of nutrients and heavy metals (Kadlec and Knight, 1996), capture of suspended sediment (Huthoff et al., 2007), and produce oxygen.

Despite the impact of vegetation on both hydrodynamics and ecology in aquatic system, the structure of vegetated flows is not well understood. Although mean flow and turbulent structures of vegetated flows were revealed by previous studies (e.g., Tsujimoto et al., 1992; Ikeda and Kanazawa, 1996; Lopez and Garcia, 1998; Nepf and Vivoni, 2000; Okabe et al., 2000; Nezu and Onitsuka, 2002; Wilson et al., 2003; Carollo et al., 2005), the knowledge cannot be applied directly to engineering practices. Also, previous studies have shown that the flow characteristics in the upper and vegetation layers of are complicated and different from each other in depth limited vegetated flows (Huthoff et al., 2007). This means that the use of the traditional approaches such as Manning, Darcy-Weisbach, and Chezy equations may lead to an inappropriate result in investigating the effect of vegetation on HSI.

In this study, a new two-layer model for open-channel flows with submerged vegetation is proposed. Simple formulas, derived from force balance and logarithmic law for the upper layer, is given. The model predicts the depth-averaged velocities in both upper and vegetation layers when the total discharge and vegetation properties are known. The proposed formula is applied to authors' and others' experimental data, showing an excellent performance.

## 2. TWO-LAYER MODEL

Depth-limited flows with submerged vegetation are featured by two distinct flow structures in the vegetation layer and the upper layer (Fig 1). That is, the (time-) mean velocity is fairly uniform in the vegetation layer, while it follows logarithmic distribution in the upper layer like open-channel flows over rough boundaries (Ikeda and Kanazawa, 1996; Nepf and Vivoni, 2000; Choi and Kang, 2004).

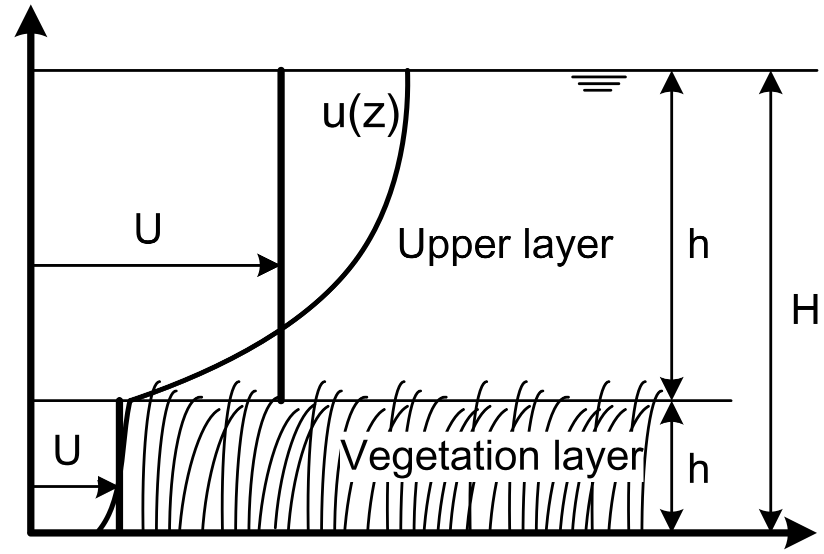

Figure 1. Schematic sketch of depth limited open-channel flows with submerged vegetation

In the upper layer, the force balance leads to

$$\tau_i = \rho g \left( h - h_1 \right) S \tag{1}$$

where $\tau_i$ is the interfacial shear stress between two layers, $\rho$ is the water density, $g$ is the gravitational acceleration, $h$ is the flow depth, $h_1$ is the height of the vegetation layer, and $S$ is the channel slope. Actually, the interfacial shear stress acts to reduce the mean velocity in the upper layer by balancing the gravity, while it accelerates the flow in the vegetation layer. Similarly, if the force balance is applied to the vegetation layer, then

$$\rho \cdot g \cdot h_1 \cdot S + \tau_i = F_D + \tau_b \tag{2}$$

where $\tau_b$ is the bottom shear stress and $F_D$ ( $= \frac{1}{2} a C_D U_1^2 h_1$ ) is the drag force due to submerged vegetation. $U_1$ is the layer averaged mean velocity of vegetation layer, $C_D$ is the drag coefficient of vegetation, and $a$ is the planting density of vegetation. From Eq. (2), a formula for the layer-averaged mean velocity of vegetation layer can be written as

$$U_1 = \sqrt{\frac{2 \cdot g \cdot h \cdot S}{a \cdot C_D \cdot h_1}} \tag{3}$$

In the present study, a uniform velocity distribution given by Eq.(3) is assumed in the vegetation layer. However, in the upper layer, it is assumed that the velocity is logarithmically distributed. That is,

$$\frac{u_2(z)}{U_1} = \frac{u_*}{U_1} \cdot \frac{1}{\kappa} \cdot \ln\left(\frac{z}{h_1}\right) + 1 \tag{4}$$

where $u_*$ is the interfacial shear velocity, $\kappa$ is von Karman constant $(=0.41)$. In Eq.(4), the logarithmic velocity profile is adjusted to satisfy that the velocity at the interface is $U_1$. Integrating Eq. (4) results in the layer-averaged mean velocity in the upper layer ($U_2$) such as

$$U_2 = \frac{1}{h_2} \int_{h_1}^{h} u(z)\,dz = \frac{u_*}{\kappa} \cdot \left[\frac{h}{h_2} \cdot \ln\left(\frac{h}{h_1}\right) - 1\right] + U_1 \tag{5}$$

where $h_2$ is the height of the upper layer $(= h - h_1)$. By integrating both Eqs. (3) and (4), the following expression for mean velocity over the entire depth is obtained:

$$U = \left[\left(\frac{\ln(d_r)}{\kappa} + \frac{C_v}{d_r}\right)\sqrt{h_2}\right] S^{1/2} \tag{6}$$

where $d_r$ is the depth ratio $(= h/h_1)$, $C_v$ is the normalized velocity in the vegetation layer $(= U_1/u_*)$. Using Eq. (6), the roughness increased by the presence of vegetation can be estimated, i.e.,

$$n_v = \frac{1}{\left(\frac{\ln(d_r)}{\kappa} + \frac{C_v}{d_r}\right) \cdot \sqrt{h_2} \cdot h^{-2/3}} \tag{7}$$

## 3. MODEL APPLICATION

Figure 2 shows the calculated versus measured mean velocities in the vegetation layer. The calculated velocity is obtained from Eq. (4), and the measured data are from various sources, i.e., from Yang and Choi (2008), Ikeda and Kanazawa (1996), Lopez and Garcia (1998), Meijer and Velzen (1999), Nepf and Vivoni (2000), and Wilson et al. (2003). The flow conditions and vegetation properties used in the present study cover a wide spectrum. Although scattered slightly, the overall agreement between calculated and measured data appears to fairly good.

Figure 3 shows the calculated versus measured mean velocities in the upper layer. The calculated velocity is obtained from Eq. (5). It can be seen that Eq.(5) predicts the mean velocity in the upper layer pretty well. That is, the mean velocity in the upper layer is determined from the depth ratio ($h/h_1$), interfacial shear velocity ($u_*$), and mean velocity in the vegetation layer ($U_1$).

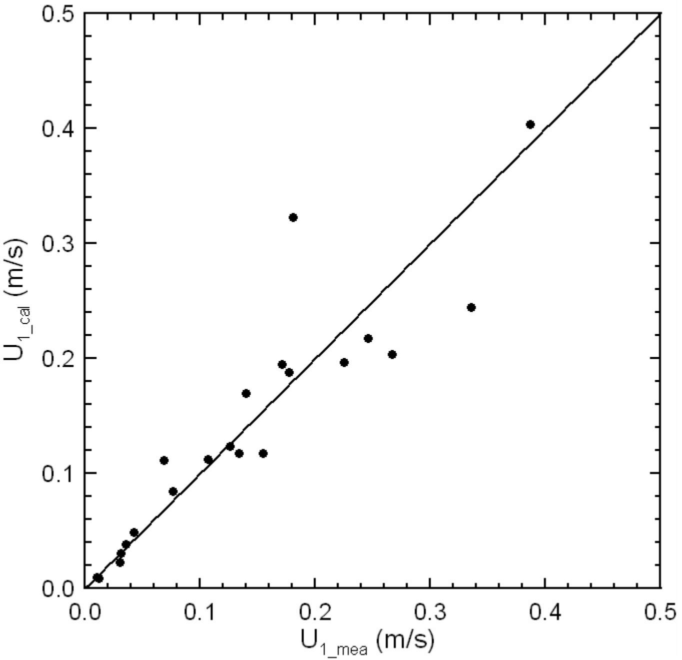

Figure 2. Comparison between calculated and measured mean velocities in the vegetation layer

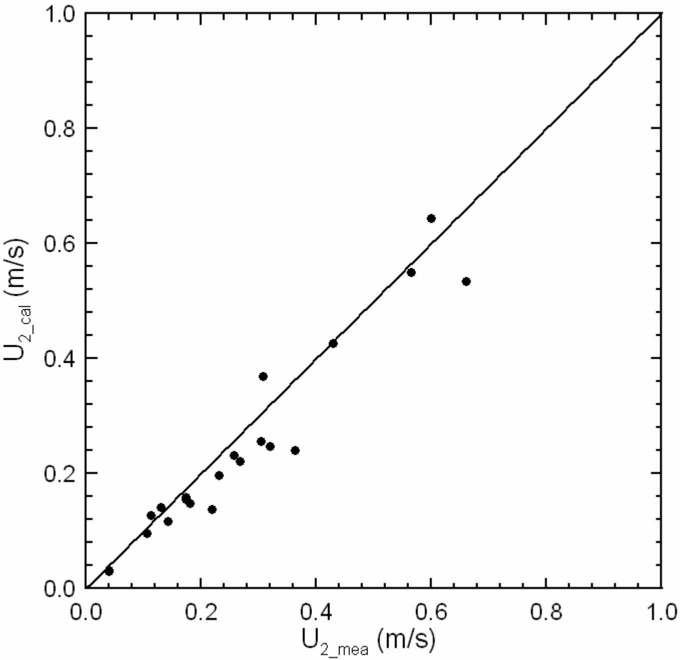

Figure 3. Comparison between calculated and measured mean velocities in the vegetation

layer

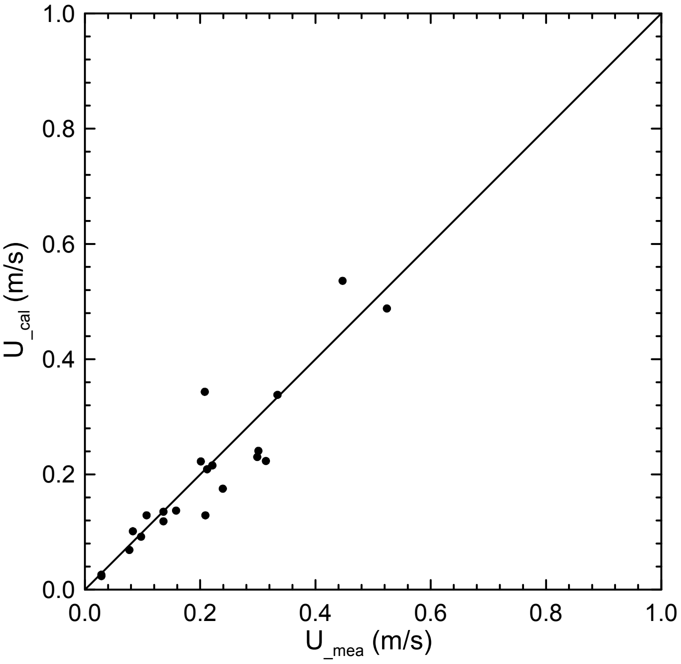

Figure 4. Comparison between calculated and measured mean velocities over the entire depth (Data form Yang and Choi, 2008)

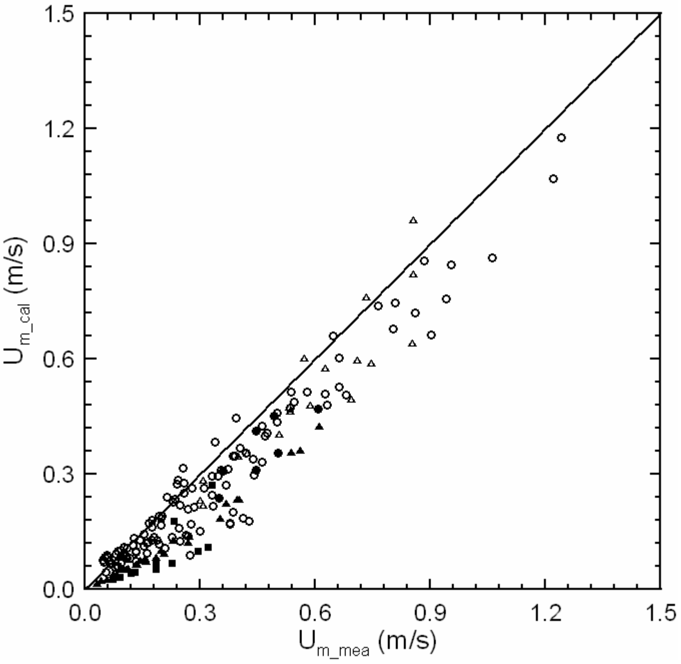

Figure 5. Comparison between calculated and measured mean velocities over the entire depth (Data from Baptist, 2005)

Calculated and measured mean velocities averaged over the entire depth are compared in Figures 4 and 5, where Yang and Choi's (2008) data and Baptist's data (2005) are used, respectively. Eq.(6) is used to estimate the mean velocity over the whole depth. Figure 4 presents that Eq.(6) performs predictions at a similar accuracy to those observed in Figures 2 and 3. However, the equation seems to under-estimate the mean velocity slightly when it is applied to Baptist's (2005) data.

Figure 6 shows the change of increased roughness due to vegetation ($n_v$) with $u_* / U_1$. It can be seen that the roughness coefficient due to vegetation increases with the interfacial shear velocity normalized by $U_1$. This is true because the roughness due to vegetation is another expression of the interfacial shear between two layers for fixed $U_1$. Also, as the vegetation density increases, the roughness due to vegetation increases with decreased $U_1$. The impact of the depth ratio is also seen in the figure.

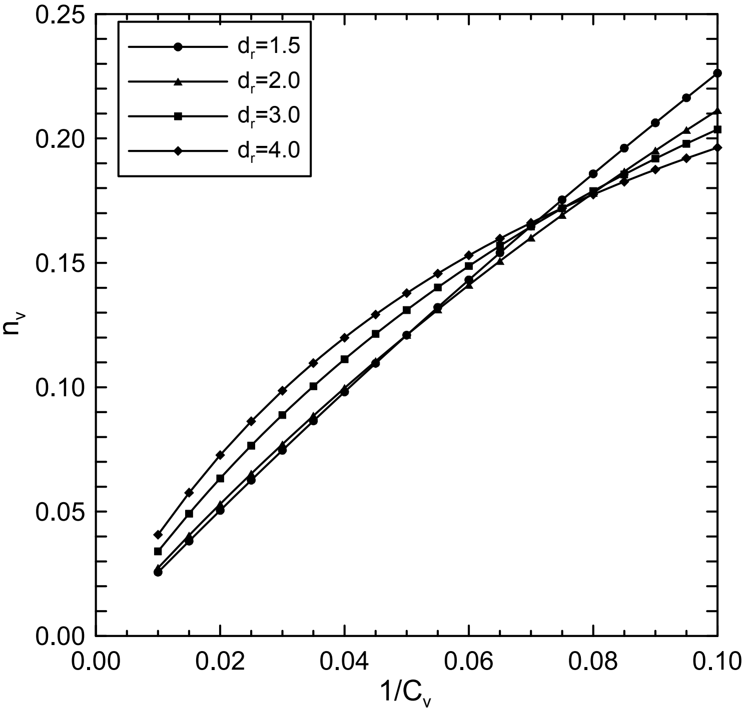

Figure 6. Manning's roughness coefficient for open-channel flows with submerged vegetation

## 4. CONCLUSIONS

This paper presented a two layer approach for depth-limited open-channel flows with submerged vegetation. Since the flow structures in the vegetation layer and the upper layers are different, uniform and logarithmic velocity distributions were assumed in the respective layers. Applying the force balance led to a velocity formula in the vegetation layer, and a log-distribution, satisfying the interfacial condition, was given in the upper layer. Averaging these two relationships over the entire depth resulted in the mean velocity formula for depth-limited channel flows with submerged vegetation. The proposed relationships were tested against various measured data for both rigid and flexible plants, exhibiting promising results.

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