Drag coefficient of vegetation in flow modeling

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INTRODUCTION

The interaction between aquatic plants and hydrodynamic force and its implication on the long-term landscape development have received intention from ecology, geology and hydraulic engineering.

Figure 1. Spartina Spp. (salt marsh grass), from Tracey Saxby (2004)

Figure 2. Spartina alterniflora meadow, from http://saltmarshlife.com

Many numerical models have been developed to quantify the vegetation effect on the hydrodynamics (Uittenbogaard [2003], Nepf [1999]) and sediment transport (Fagherazzi [2012] for a review). The vegetation resists flow, damps waves and alters the turbulent intensity predominantly though exerting additional drag force on the water particles passing it. In these models, the drag force is quantified by the quadratic law (Equation 1.) originated from Morison [1950], which uses a drag coefficient to characterize the average drag force provided by one stem:

$$F(z) = \frac{1}{2}\rho_0 C_D(z)a(z)\left|u(z)\right|u(z) \quad [N/m^3] \qquad (1)$$

Where ρ_0 is the water density, *u(z)* is the horizontal flow velocity at height *z*. *a (z)* is defined as:

$$a(z) = n(z)d(z) \quad [\mathrm{m}^{-1}] \qquad (2)$$

Where *n (z)* and *d (z)* are the number of stems per unit area [m-2] and average stem diameter [m] respectively. The drag coefficient C_D is the measure of the ability of the plants to reduce the hydrodynamic force and engineering its own environment (Bouma [2010]) and the key to the success of these models. The C_D for an isolated cylinder is well established (Sumer and FredsØe [2006]). But C_D value for multi-plant structures is difficult to determine, because it is closely related to both the plants property and the local hydrodynamic conditions. But many experiment studies have showed that the C_D for vegetation varies greatly according the vegetation density, diameter, stiffness as well as the hydrodynamic conditions. (Cheng [2011], Tanino [2008]) But in all these studies, the C_D value is derived from one-dimensional momentum equation under uniform flow. In nature, the vegetation structures vary greatly in verticals in terms of *a (z)* (see Figure 1. and 2), which implies that the C_D value should be a function of depth as well. In this study, the hypothesis is made that the C_D relation proposed by Cheng [2011] can be modified into depth-variable relation. The modified relation depends on the local flow conditions and canopy properties in the vertical. This relation is implemented in an iterative scheme of a *1DV* flow model. The modeling results are compared with experiment data of flow through rigid vegetation.

METHODS

Cheng [2011] proposed a special-defined Reynolds number R_v by using a vegetation-related hydraulic radius r_v as its length scales. This Reynolds number is modified to count the flow and canopy that vary vertically:

$$\mathrm{R}_v(z) = \frac{u(z)r_v(z)}{v} \quad [-] \qquad (3)$$

$$\mathrm{r}_v(z) = \frac{[1-\phi(z)]\Delta h}{a(z)\Delta h} = \frac{1-\phi(z)}{n(z)d(z)} \quad [\mathrm{m}] \qquad (4)$$

$$\phi(z) = \frac{\pi}{4}n(z)d(z)^2 \quad [-] \qquad (5)$$

v is the Kinematic viscosity, r_v *(z)* is defined as the ratio of the volume occupied by water per unit area in a certain depth (Δh) to the total front area of vegetation per unit area. ϕ *(z)* is the solid area of vegetation per unit area. Since the vegetation Reynolds number R_v (z) varies with flow velocity *u (z)* and plant characters *r (z)* in depth, the C_D is modified to be a function of *z* as well. The original formulation (Cheng, [2011]) is modified (which is the new aspect of this paper):

$$C_D(z) = \frac{50}{R_v^{0.43}(z)} + 0.7[1-\exp(-\frac{R_v(z)}{15{,}000})] \quad [-] \qquad (6)$$

Hence, C_D in Equation (1) is substituted by Equation (6) by an iterative scheme in the *1 DV* model (Uittenbogaard, [2003]). The vegetation is schematized as rigid cylinders and the following vegetation-related drag force has been included explicitly. The model is used to revisit previous flume experiments. The predicted mean velocity profile and C_D are compared with the experiment data in previous studies.

RESULTS

The results of C_D value and the velocity profiles are shown in Fig 3. and 4. The vertical axis is scaled by the vegetation height *h*. Overall, Equation (6) gives a fairly good prediction and the results of velocity fit the measured data well. Fig 3. shows when R_v is in the range of 1×10^4-5.6×10^5 where C_D is *1-1.2*, the prediction of fits well with the experiment data from Patil [2009]. But when R_v is small (1×10^3-1×10^4), the relation underpredicts the C_D value, resulting in higher velocity in the canopy (*z/h* ≤ 1) than the experiment data from Ghisalberti and Nepf [2004] (see Fig 4).

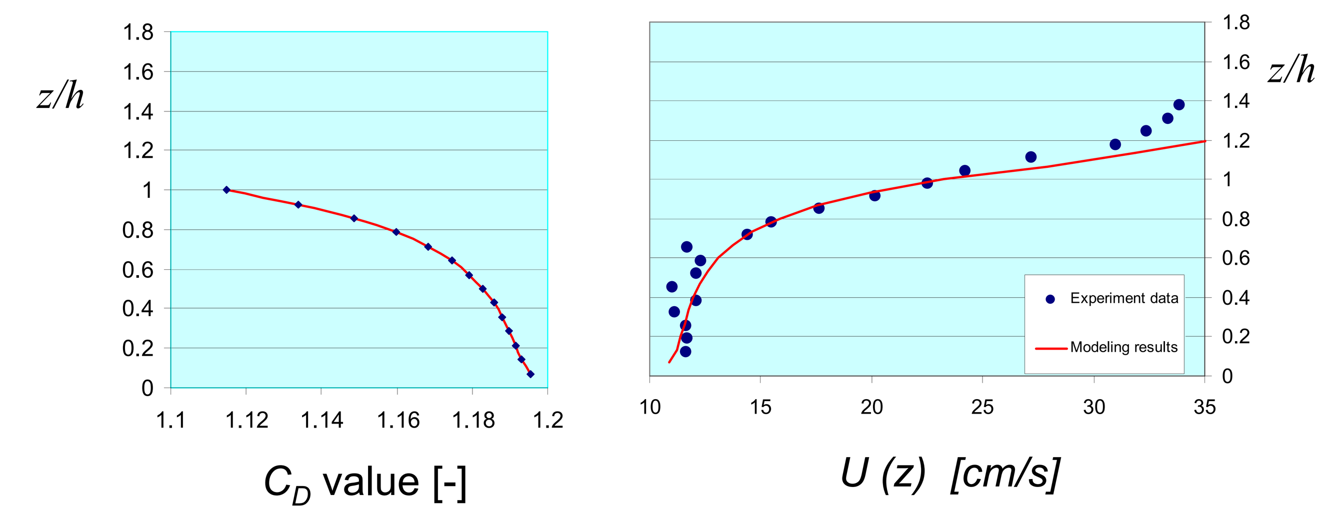

Figure 3. The left plate is the model results of C_D value; The right plate is the comparison of velocity profile *u*

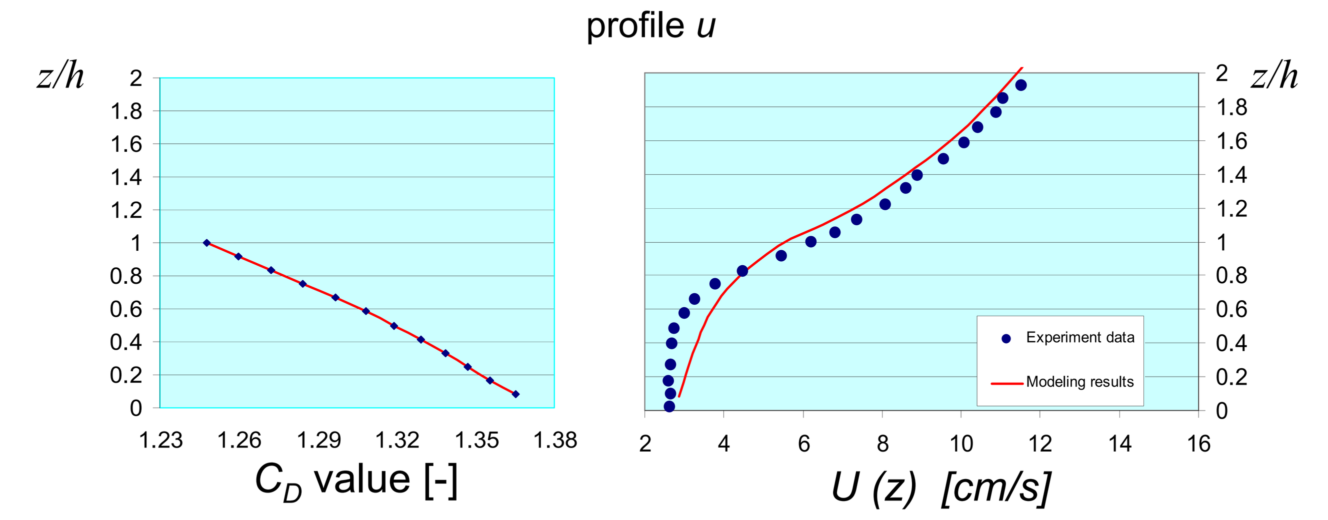

Figure 4. Same as above

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