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Numerical modeling of free surface flow over submerged and highly flexible vegetation

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ABSTRACT

Vegetation in rivers, estuaries and coastal areas is often submerged and highly flexible. The study of its interaction with the ambient flow environment is important for the determination of the discharge capacity, morphological characteristics and ecological conditions of the water course where it grows. In this work the hydrodynamics of submerged flexible vegetation with or without foliage is investigated by using a 3D numerical model. Flexible vegetation is modeled by momentum sink terms, with the velocity-dependent stem height determined by a large deflection analysis which is more accurate than the previously used small deflection analysis. The effect of foliage on flow resistance is expressed in terms of the change in the product of the drag coefficient and the projected area, which is supported by available experimental data. The computed results show that the vertical profiles of the mean horizontal velocity and the vertical Reynolds shear stress are correctly simulated. The temporal variation of the stem deflection follows closely that of the velocity and the 'Honami' phenomenon can be reproduced. The numerical simulations also confirm that the flexibility of vegetation decreases both the vegetation-induced flow resistance force and the vertical Reynolds shear stress, while the presence of foliage further enhances these reduction effects.

1. Introduction

Vegetation contributes to the sustainable development of aquatic environments. It provides food and shelter to many organisms and controls the ecological system in rivers, estuaries and coastal areas. In estuarine and coastal areas, vegetation is often submerged and with high flexibility. It will deflect and interact with the ambient flow environment. An accurate prediction of the interaction between the water flow and the flexible vegetation will be required for the determination of the discharge capacity, morphological characteristics and ecological conditions of the water course where the vegetation grows.

Numerical models for flow through vegetation with rigid stems have been developed and used extensively and can be subdivided into RANS (Reynolds Averaged Navier–Stokes equations) models and LES models. For RANS models, Shimizu and Tsujimoto [1], Lopez and Garcia [2], and Leu et al. [3] employed the two-equation k–ε closure of turbulence; Naot et al. [4] and Choi and Kang [5] used the multi-equation anisotropic Reynolds stress closure of turbulence. For LES models, Patton et al. [6] used the one-equation k-l sub-grid turbulence closure, Cui and Neary [7] used the Smargorinsky sub-grid scale turbulence closure with dynamic adjustment of the closure coefficient.

For flexible vegetation with prismatic stems and relatively high stiffness, its deflection can be predicted by the small deflection analysis of cantilever beam [8]. Kutija and Hong [9] developed a one-dimensional model utilizing Timoshenko's theory to determine the bending of the vegetation. The work was continued by Erduarn and Kutija [10] and a quasi-three-dimensional method was developed. Velasco et al. [11] employed the classical elastic beam equation to compute the deflection of vegetation stems with moderate flexibility. A 1D model has been developed to compute the vertical profiles of the velocity and Reynolds stress. Ikeda et al. [12] developed a 2D LES model to simulate the wavy motion of flexible vegetation. In the model a complex 'plant grid' is used to track the movement of each stem and the equation of motion of each flexible stem is solved directly. This approach is sophisticated but computationally expensive.

Physical experiments on the determination of flow resistance due to vegetation with foliage have been carried out by some investigators. Fathi-Maghadam and Kouwen [13] and Kouwen and Fathi-Maghadam [14] measured the drag forces on several species of vegetation, and related the product of the drag coefficient C_d and the leaf area index (A/a, A = total flow projected area of vegetation, a = horizontal area occupied by the vegetation) to the flow velocity. A decreasing trend of the parameter C_dA/a with

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the flow velocity was obtained. James et al. [15] attempted to isolate the effects of drag coefficient and projected area by constructing models of artificial stems with leaves set in fixed and deformed shape in accordance with the observations of flows through real reeds and bulrushes. By defining the drag coefficient in terms of the true projected area, the value of the drag coefficient is less varying. Wilson et al. [16] directly measured the drag forces on individual pieces of vegetation to determine the contribution of the foliage of a plant to the total drag force on the plant. They observed the decreasing trend of the parameter C_dA with the flow velocity. This was explained by that the highly flexible foliage will streamline with the flow and reduce the overall drag coefficient as well as the projected area.

Extensive field and laboratory studies of flows in vegetated watercourses have been carried out recently [17–26]. In particular, it was observed that under certain flow conditions organized vertical flow structures occur at the tip of the vegetation. The interaction between the flow and the flexible stems of the vegetation produces a wavy motion of the plants called 'Honami' [12] or 'Monami' [27]. Ikeda and Kanazawa [28] and Ghisalberti and Nepf [27] showed that Honami is due to the Kelvin–Helmholtz instability of flow at the inflection point of the vertical profile of the mean velocity located at the tip of the vegetation. The instability generates coherent vortices which are transported downstream and cause wavy motion of the vegetation.

For vegetation with high flexibility the small deflection analysis may not be accurate enough to predict its deflection under water flow. In this work a large deflection analysis is employed in which the Euler–Bernoulli Law for the bending of a slender beam is used to determine the large deflection of a plant stem. The resulting nonlinear equation is solved iteratively by a finite difference scheme. The fluid load–deflection relationship is obtained a priori and input into a 3D model. The time and space varying velocity field is then computed and the interaction of the flexible vegetation with the fluid environment is studied.

2. Large deflection of a plant stem

It is assumed that a piece of vegetation can be represented by an inextensible non-prismatic slender beam of length L. The water flow produces variable distributed loads $q_x(s)$ on the beam along the x direction (Fig. 1). The equilibrium of forces and momentum gives

$$\frac{d^2M}{ds^2} + \frac{dM}{ds}\frac{\frac{d\delta}{ds}\frac{d^2\delta}{ds^2}}{\left[1-\left(\frac{d\delta}{ds}\right)^2\right]} = -q_x(s)\sqrt{1-\left(\frac{d\delta}{ds}\right)^2} \tag{1}$$

where M = moment, δ = deflection in x-direction, s = local ordinate along the beam. The Euler–Bernoulli law states that the local bending moment is proportional to the local curvature

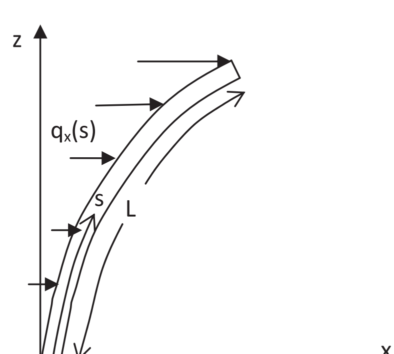

Fig. 1. Definition sketch of large deflection of a beam subjected to distributed loading.

$$M(s) = EI(s)\frac{\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2} \tag{2}$$

where E = flexural stiffness (N/m^2), I = second moment of area (m^4). Combining Eqs. (1) and (2), a fourth order nonlinear equation in δ is resulted

$$\frac{d^2}{ds^2}\left[EI(s)\frac{\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2}\right] + \frac{d}{ds}\left[EI(s)\frac{\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2}\right]\frac{\frac{d\delta}{ds}\frac{d^2\delta}{ds^2}}{1-\left(\frac{d\delta}{ds}\right)^2} = -q_x(s)\sqrt{1-\left(\frac{d\delta}{ds}\right)^2} \tag{3}$$

The equation can be solved by using a quasi-linearized central finite difference scheme. Details can be found in AL-Saddar and AL-Rawi [29].

The vegetation stem is assumed inextensible, the total length of the stem remains constant (=L). By dividing the stem into m equal segments, with segment length Δs constant, the z-ordinate of the ith node is given by

$$z_i = \sum_{j=1}^{i}\sqrt{\Delta s^2 - (\delta_i - \delta_{i-1})^2} \tag{4}$$

The deflected height of the stem is then equal to z_m.

To verify the model, experimental data obtained by Belendez et al. [30] for the large deflection of a cantilever beam under a combined load consisting of a uniform distributed load and a concentrated load F at the free end are used. The parameters are: L = 0.4 m, $I = 1.33 \times 10^{-13}$ m^4, E = 200 GPa, $q(s)$ = 0.758 N/m, the free-end concentrated load varies between 0 and 0.588 N. In the computation the beam is subdivided into 60 grids. The concentrated load is represented by an equivalent distributed load at the end point. The measured and computed free-end deflections are tabulated in Table 1. It can be seen that the differences between the two set of results are within 2%, with the average value of 1%.

In a 3D computational region, it is not efficient to directly compute the large deflection of individual stems since the vegetation density can be very high. Instead, an empirical approach is adopted in this study. For a beam subjected to uniform lateral distributed load $q(z) = q_x(s)ds/dz$, the dimensional analysis gives the following expression

$$\frac{h}{L} = \phi\left(\frac{qL^3}{EI}\right) \tag{5}$$

where h = deflected height of the beam. The empirical form of the function ϕ can be obtained by using the above model to compute a sufficient large number of cases with different values of the non-dimensional parameter $q_n = qL^3/EI$. The results are plotted in Fig. 2 (constant u profile) and a piecewise sixth order polynomial is used to approximate the function ϕ within the practical range of values of qL^3/EI. The best-fit polynomial is given as follows.

For $q_n \leqslant 100$,

Table 1
Large deflection of a cantilever beam under combined loading.

F (N)	δ (m) experimental [30]	δ (m) computed	Difference (%)
0.000	0.089	0.0895	0.6
0.098	0.149	0.1501	0.7
0.196	0.195	0.1940	0.5
0.294	0.227	0.2251	0.8
0.392	0.251	0.2475	1.4
0.490	0.268	0.2641	1.5
0.588	0.281	0.2767	1.5