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Laboratory study of the effect of vertically varying vegetation density on waves, currents and wave-current interactions

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ABSTRACT

Under the influence of vegetation, waves, currents, turbulence as well as sediment processes are all changed, which significantly affect aquatic environment. Vegetation appears spatially heterogeneous in terms of vegetation density in most natural wetlands. However, how vertical heterogeneity of vegetation canopy affects turbulence under waves and currents is still not well understood. In this paper, the effects of different vegetation densities (i.e. sparse, dense and vertically-varying density) on vegetation-induced wave attenuation, mean flow adjustment as well as turbulence are studied through laboratory experiments. For regular waves, higher vegetation density results in smaller wave transmission coefficients and local wave heights. The difference between the effects of vertically uniform and varying vegetation density on wave height decay is significant for deep water waves and insignificant for intermediate water waves. The vertically varying vegetation density slightly changes the wave-averaged velocity distribution, producing reverse flows within the canopy. Turbulence intensity decreases more significantly with increasing water depth in the case with vertically varying vegetation density. For unidirectional flow, the vertically varying vegetation density increases the vertical gradient of mean streamwise velocity compared with the emergent uniform vegetation. The time series of u oscillates relatively stronger near bottom, and causes higher *TKE*, which is different with that in oscillatory flow. Compared with the submerged uniform vegetation, the vertical variation of mean velocity affected by vegetation with vertically varying density is smaller in both pure current and wave-current flow. Affected by dense submerged vegetation, the mean velocity of combined wave-current flow is significantly lower than that of pure current, while it is reduced near the bottom and increased in the upper layer comparing with that of pure current under the influence of sparse submerged vegetation. *TKE* values in wave-current flow is promoted in the upper layer with coexisting waves in the case of submerged uniform vegetation, while it is barely affected near the bed. In the case with vertically varying vegetation density, *TKE* values in the wave-current flow are slightly decreased than that in the pure current condition, especially near the bottom.

1. Introduction

Aquatic vegetation is ubiquitous in riverine and coastal environment. It plays an important role in water environment by acting as a natural barrier to protect river channel/coastlines, and a stabilizer of riverbed/seabed. With the presence of vegetation, waves, currents, turbulence as well as sediment processes can be greatly impacted. Under unidirectional currents, vegetation can reduce mean flow and compress turbulence level [1], subsequently promoting sedimentation and the retention of suspended sediments [2–4]. In coastal wetlands, vegetation can effectively dissipate wave energy [5–9], reduce storm surge [10–12] and attenuate tsunami attacks [13,14].

Vegetation effects on waves and currents have drawn wide attention in the past decades. For vegetated open channel flow, most existing experimental and numerical studies have focused on the effects of either rigid or flexible vegetation with uniform stem density on mean flow and turbulence [1,15–19]. A review of physical processes involved in flow through a vegetation canopy is presented by Nepf in 2012 [20]. The key points are summarized as follows. Mean flow can be greatly reduced by a vegetation canopy. Vegetation-induced turbulence is generated by both the individual stems (stem-scale turbulence) and the canopy as a whole (canopy-scale turbulence). The magnitude of turbulence strongly depends on the density of the canopy and the geometry of individual stems. A sparse canopy can generate lower stem-

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scale turbulence, but allow canopy-scale eddies to penetrate deeply into the vegetated water column. A dense canopy generates higher stem-scale turbulence and constrains canopy-scale turbulence in a limited penetration depth near the top of the vegetation.

Past studies on wave-vegetation interactions have been mainly focused on the damping effects of rigid vegetation on wave energy. In these studies, semi-empirical formulations for wave attenuation in vegetated region were derived based on linear wave theory and conservation of wave energy (e.g., [5,7,21]). Besides theoretical research, laboratory experiments and numerical simulations have also been conducted. For example, Augustin et al. [8], Anderson and Smith [22], Hu et al. [23] and Losada et al. [24] carried out extensive experiments in wave flumes to study wave attenuation induced by vegetation canopies. Valuable data have been collected for validation of theoretical and numerical models. Numerical simulations of vegetation-induced wave damping relied on different wave models, including wave spectrum model [25], Boussinesq wave-resolving model [8], non-hydrostatic wave model [9,26,27] and Navier-Stokes solver [28]. Compared to unidirectional flow, wave-induced current (oscillatory flow) through the vegetation canopy is more poorly understood. The analytical and experimental studies conducted by Lowe et al. [29,30] have revealed that the oscillatory flow generates a higher in-canopy flow compared to unidirectional flow, thus enhancing rates of mass transfer from the canopy elements. Luhar et al. [31,32] found evidences from laboratory experiments and field observations that oscillatory flow within the vegetation canopy may generate a mean flow in the direction of wave propagation, similar to the streaming observed in wave boundary layers. These features in vegetated oscillatory flow may affect sediment dynamics in wave boundary layer.

All the above-mentioned studies consider vegetation canopies with uniform stem density. However, vegetation appears spatially heterogeneous in terms of vegetation density in most natural wetlands. Lemein et al. [33] found that, for a typical salt marsh vegetation canopy, the above ground biomass shows a linear distribution with higher density near the bottom. Numerical study by Wu et al. [34] revealed that vertically varying vegetation density can generate much higher level of turbulence within the canopy compared to vertically uniform vegetation density because the vertically varying vegetation density produces a number of shear layers throughout the vegetated water column. However, laboratory observations are lacking to draw further conclusions on how vertical heterogeneity of vegetation canopy affects turbulence within the canopy under waves and currents.

In this paper, the effects of different vegetation densities (i.e. sparse, dense and vertically varying density) on vegetation-induced wave attenuation, mean flow adjustment as well as turbulence are studied through laboratory experiments. The aim is to investigate the effects of vertical heterogeneity on hydrodynamics in natural wetland settings. Due to the complexity of the problem, rigid vegetation neglecting swaying and bending is considered. The stiff wooden cylinders are employed in the experiments. Cylinders with different heights are used to construct the canopy with vertically varied vegetation density, which is increasingly higher from the bottom. The paper is organized as follows. The theoretical background about flow affected by vegetation is discussed in Section 2. Section 3 describes the flume setup and measurements design in laboratory. Section 4 presents the results of the laboratory measurements. Wave transmission coefficient, bulk drag coefficient, and turbulent kinetic energy are calculated and discussed in this section. The paper concludes in Sections 5.

2. Theoretical background

To quantify and compare the effects of different vegetation densities on waves and currents, wave transmission coefficients, bulk drag coefficient as well as turbulence are evaluated for different experimental tests. This section presents the theoretical background of these quantities.

When wave travels over a vegetated area, there are two forces exerting on plant stems: drag force and inertia force. Because the inertia force does not contribute any work over entire oscillatory flow period [21], wave energy dissipation is mainly caused by the work done by the drag force. The vegetation-induced drag force acting on the water column could be expressed by a Morison-type equation by neglecting swaying motion and inertial force. The horizontal force per unit volume is given by

$$F_D = \frac{1}{2}\rho \bullet C_D \bullet d \bullet l_s \bullet N \bullet U\ |U| \tag{1}$$

where F_D is the drag force,? ? is the density of the fluid, C_D is the bulk drag coefficient, d is stem diameter, l_s is stem length under submerged vegetation condition ($l_s = h$, under emergent vegetation condition), U is the measured instantaneous horizontal velocity, N is the number of vegetation stems per unit horizontal area.

The influence of vegetation on wave attenuation is evaluated by wave transmission coefficient, which is given by

$$K_v = \frac{H(x)}{H_0} = \frac{1}{1 + \beta x} \tag{2}$$

where $H(x)$ is local wave height at a horizontal distance x from the leading edge of the vegetation, H_0 is the wave height at the leading edge of the vegetation (incident wave height), β is a damping factor, which has been formulated by [21] by using linear wave theory and approximating the vegetation as rigid vertical cylinders. The formulation is given by

$$\beta = \frac{4}{9\pi} C_D d N H_0 k \frac{sinh^3 k l_s + 3 sinh k l_s}{(sinh2kh + 2kh) sinhkh} \tag{3}$$

where k is the wave number.

Previous studies found that the bulk drag coefficient C_D was closely related to the Reynolds number [35].

$$R_e = \frac{u_{max} d}{\nu} \tag{4}$$

where ν is the kinematic viscosity of water ($1.011 \times 10^{-6}\,\mathrm{m^2/s}$), d is the characteristic length taken as the cylinder diameter, and u_{max} is the characteristic velocity taken as the horizontal orbital wave velocity estimated at the still water surface from linear wave theory and defined as

$$u_{max} = \frac{\pi H}{T} \cdot \frac{cosh(kh)}{sinh(kh)} \tag{5}$$

The Keulegane-Carpenter number (KC) is used to represent the importance of the drag force compared to the inertial force for oscillatory flow.

$$KC = \frac{u_{max} T}{d} \tag{6}$$

It is also common to use the Ursell number (U_r) to characterize the balance between the wave steepness δ and the relative water depth kh.

$$U_r = 8\pi^3 \frac{\delta}{(kh)^3} \tag{7}$$

To evaluate the intensity of turbulence, the turbulent kinetic energy (TKE) is commonly calculated using the measured instantaneous velocity by Eq. (11).

$$u = \overline{u} + u' \tag{8}$$

$$v = \overline{v} + v' \tag{9}$$

$$w = \overline{w} + w' \tag{10}$$

$$TKE = \frac{1}{2} \cdot (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{11}$$

where u, v, w are measured instantaneous velocities in x, y, z direction.