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Bulk drag of a regular array of emergent blade-type vegetation stems under gradually varied flow

A.O. Busari, C.W. Li *

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, HKSAR, China

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Abstract

The drag induced by flow through vegetation is affected by the velocity, shape of vegetation stems and wake interference among stems. To account for the interference effects, previous works generally related the bulk drag coefficient of vegetation to the solid volume fraction ϕ of the vegetated zone, and the trends of the results were found to be inconsistent. In this work, a systematic laboratory study has been carried out to investigate the effect of the distribution pattern of vegetation stems on the hydrodynamics of gradually varied flow through emergent blade-type vegetation. The finite artificial vegetation patches of solid volume fractions ranging from 0.005 to 0.121 have been used and the stem Reynolds number ranges from 500–2600. The longitudinal water surface profiles have been measured, and the effect of increasing roughness density with respect to varying longitudinal and lateral spacing under the flow conditions is examined. The momentum equation that relates the vegetation resistant force and water surface profile has been used to obtain the mean bulk drag coefficient C_d of the canopy. The results show that C_d decreases with increasing stem Reynolds number, decreases with increasing ϕ at fixed lateral spacing due to sheltering effect, and increases with ϕ at fixed longitudinal spacing due to channeling effect. An empirical equation has been obtained relating C_d to the lateral and longitudinal spacing instead of ϕ.

Keywords: Drag coefficient; Interference effects; Emergent vegetation; Gradually varied flow

1. Introduction

Vegetation occurs in riverine environment and is commonly found along the banks, in channel or on the floodplain. It has a significant influence on the behavior of the fluvial system. The benefits rendered by vegetation such as storm surge protection, providing habitat for aquatic animals, bank/channel stabilization and water quality improvement motivate the research of vegetated flows. For river and coastal management, the planting of vegetation along channels and coastal areas increases the hydraulic resistance, reduces flow speed and hence erosion. The increasing hydraulic resistance is due to the viscous and pressure drags on the plants. The pressure drag is dominating and proportional to the square of the velocity, with the constant of proportion called the drag coefficient. The vegetation induced drag and the associated drag coefficient depends on the properties of vegetation, such as areal density, flexibility, patchiness, age, seasonality, and foliage (e.g., Li and Xie, 2011, Nikora et al., 2008, Stone and Shen, 2002; Tanino and Nepf, 2008, Wu et al., 1999, Yang and Choi, 2009, Zeng and Li, 2014). The mean drag coefficient of a vegetation zone is then called the bulk drag coefficient C_d (e.g., Nepf, 1999). In the simulation of vegetated flows, C_d is an important input parameter to the theoretical, (semi)empirical or numerical model and its accurate estimation is essential (Busari and Li, 2014).

The fact that the areal density of vegetation will affect the drag coefficient has been recognized in previous studies, including Fathi-Moghadam and Kouwen (1997), Nepf (1999), Armanini et al. (2005), James et al. (2004), Righetti and Armanini (2002), Kouwen and Fathi-Moghadam (2000). Various studies suggested there are different trends for the bulk drag coefficient against areal density of vegetation (λ) for cylinder arrays. Nepf (1999) developed a wake interference model to account for the reduction of drag coefficient of a cylinder in an array. The model predicts that the bulk drag coefficient

* Corresponding author. C.W. Li, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, HKSAR, China. Tel.: +852 27666043; fax: +852 23346389.

E-mail address: cecwli@polyu.edu.hk (C.W. Li).

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decreases with the increase in solid volume fraction ϕ. The model results were supported by some available experimental data (Kays and London, 1955; Zdravkovich, 1993).

On the contrary, Stone and Shen (2002) found that the bulk drag coefficient increases with the solid volume fraction for an array of cylinders with staggered arrangement. The use of the velocity between the stems as the velocity scale reduces the bulk drag coefficient, which becomes closer to that of an isolated cylinder. Tanino and Nepf (2008) carried out experiments to determine drag in a random array of cylinders and found that the bulk drag coefficient increases with ϕ. The bulk drag coefficient decreases with the increase in stem Reynolds number in the range of Re = 65–685. Kothyari et al. (2009) measured directly the drag on a single cylinder within a staggered array of cylinders and found that the stem drag coefficient increases logarithmically with ϕ. The bulk drag coefficient slightly decreases with the increase in stem Reynolds number Re in the range of Re = 1000–5000. Cheng and Nguyen (2011) reported the similar trend and determined the C_d-Re relationship for cylinder arrays using a vegetated-related hydraulic radius as the characteristic length scale. Cheng (2013) applied the C_d-Re curve for an isolated cylinder to an array of cylinders using a generalized Reynolds number.

Most of the previous studies focused on rigid cylinders under uniform flow conditions. For emergent vegetation with high areal density, uniform flow condition seldom occurs and the flow will be gradually varied. Li and Tam (2002) have studied simulated semi-rigid vegetation (using black rubber rods) under gradually varied flow condition with gentle bed-slope of 1:1000. The longitudinal momentum equation was used to determine the mean bulk drag coefficient through the matching of the computed and measured water surface profiles. While the use of circular cylinders to simulate vegetation stems is common, some species of vegetation are of blade type. There is not much study of vegetated flows with blade type elements. Available works include Nezu and Sanjou (2008), Yang and Choi (2009). All these works focus on the flow and turbulent characteristics of the vegetation under submerged condition.

Previous works indicate that the bulk drag coefficient may not solely dependent on the solid volume fraction. The distribution pattern of the stems in the array will be important. The present study aims to investigate the interference effects among the vegetation stems through laboratory flume measurements of gradually varied flow through blade-type vegetation elements. The longitudinal and lateral spacing between adjacent vegetation elements are changed in different sets of experiments to identify the mechanism of flow interference. The bulk drag coefficient is determined based on the longitudinal momentum equation for gradually varied flow. An empirical formula relating C_d and the longitudinal and lateral stem spacing is proposed.

2. Wake interference effects of multiple stems

Vegetation of finite length and width commonly occurs along river channels. The flow is often nonuniform and the water surface profile is gradually varied. The key parameter to be determined is the bulk drag coefficient for each stem. The total drag consists of the shear force and the pressure drag, which is affected by the presence of multiple stems that alter the flow conditions.

The flow around a single stem will separate at certain location on the stem surface, creating a low pressure wake region behind the stem. The pressure difference between the windward and leeward surfaces generates the pressure drag. In addition, the flow will exert a viscous force on the stem surface and generates a shear friction drag on the stem. The total drag consists of the pressure drag and the friction drag. For bluff bodies including vegetation stem, the pressure drag is much larger than the friction drag.

In an array of stems, the phenomenon is complicated. If a stem is situated behind an adjacent stem, it will be subjected to a lower velocity of flow due to the blocking effect of the upstream stem. If it is located closely to the upstream stem, the wake behind the upstream stem will be interfered with the eddy scale limited by the stem spacing. The reduction in velocity and reduction in the eddy size will lower the pressure drag. The overall drag reduction effect is called the sheltering effect.

On the contrary, if a stem is situated close to an adjacent stem transversely, the width of the flow path will be narrowed. The velocity of flow in the narrow gap will be significantly increased due to the continuity requirement. A significant portion of the pressure energy will be converted into the kinetic energy, resulting in a further decrease of the pressure at the wake region behind the stem. The drag will then be increased due to the larger pressure difference across the stem. The overall drag increase effect is called the channeling effect.

Understanding the "*sheltering*" and "*channeling*" effects can be useful for river restoration. The former can be used as an erosion control mechanism and provide a favorable habitat for aquatic animals. The latter can enhance solute transport and reduce sediment accumulation. To strike a balance between the ecological preservation and hydraulic resistance reduction, vegetation management can take account the interference effects among individual stems.

3. Theory

The drag force on a piece of vegetation due to fluid flow can be expressed as

$$F_d = -\mu \iint_{S_c} \frac{\partial \vec{u}}{\partial n} dS + \iint_{S_c} p \cdot \vec{n} dS \tag{1}$$

Where μ ($N\ s/m^2$) is the viscosity, $\vec{u}$ *(m/s)* is the velocity vector at the vegetation surface, $\vec{n}$ is the outward unit normal vector on S_c, S_c (m^2) denotes all surfaces, p (N/m^2) is the pressure. On the right hand size of Eq. (1), the first term represents the viscous shear force and the second term represents the pressure force due to the wake. In general, the viscous shear force is small and a nondimensional drag coefficient is used to characterize the drag force as follows:

$$C_{d1} = \frac{F_d}{0.5 \rho A_p U^2} \tag{2}$$