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Effects of intertidal wetland vegetation and suspended sediment on flow velocity profiles and turbulence characteristics

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A B S T R A C T

Intertidal wetland vegetation has an important role in flow structure, suspended sediment movement and geomorphology evolution. This study performed a flume experiment using *Scirpus mariqueter* from the field to investigate the impact of wetland vegetation on flow structure. The experimental plans were designed based on the relative depth of flow depth to vegetation height, i.e., non-submerged, moderately submerged and completely submerged conditions. Based on the measured Reynolds stress distribution, the classical mixing length hypothesis was used to derive the new velocity profiles inside the canopy. The good agreement of the results demonstrated that this method can be used to predict the velocity distribution of the submerged flow with flexible vegetation. Through statistical analysis combined with the theory of the boundary layer and sediment movement dynamics, the turbulence intensity and fine sediment distributions within the canopy were also obtained. The results reveal the mechanism of the effect of vegetation on the water and sediment of tidal flat in theoretical terms and enhance the understanding of hydrodynamics within the canopy.

1. Introduction

Vegetation in intertidal salt marshes has large effects on hydrodynamics and sediment movements due to the interaction mechanism between flow and vegetation (Luhar et al., 2008). This issue has been the focus of many studies, especially of flow structure, shear force and sediment movements (Wilson et al., 2003; Graham et al., 2007). With regard to flow structure, many researchers have paid a great deal of attention to the vertical velocity distribution (velocity profile), Reynolds stress, turbulence characteristics and flow resistance under non-submerged (Carollo et al., 2002; Wu, 2008) and completely submerged conditions (Järvelä, 2005; Nikora and Nikora2010). Normally, different structural characteristics of plants have different effects on the flow velocity, Reynolds stress and flow resistance. These structural characteristics include uniformity (Neumeier, 2005), arrangement (Järvelä, 2004), planting slope (Davidson-Arnott et al., 2012; Gorrick and Rodríguez, 2012), planting density (Plew et al., 2008; Vandenbruwaene et al., 2011) and flexibility (Järvelä, 2002; Galema, 2009). The generally accepted results indicate that the velocity profile deviates from logarithmic, exponential or power-law distributions (Kotey et al., 2003). The velocity distributions in vegetated channels can even be grouped into four layers with different equations (Chen and Kao, 2011). It has been proven that the boundary layer theory can be employed to represent the velocity profile of the flow (Ghisalberti and Nepf, 2002), and Huai et al. (2009) proposed a new formula for velocity distribution, including three hydrodynamic regimes of rigid vegetation applying the modified mixing length model.

In regard to the flow turbulence, it has been noted that aquatic plants can exert a limited influence on the flow structure (Nepf and Vivoni, 2000; Tanino and Nepf, 2008). A peak of Reynolds stress is reached near the top of the plant canopy, and new upper and lower boundary conditions are formed (Poggi et al., 2004; Afzalimehr et al., 2010). Nepf and Finnigan conducted systematic studies involving combining experiments with the theory of turbulence and stated that the turbulence is greatly related to vegetation characteristics (Nepf, 1999; Finnigan, 2000; Finnigan et al., 2009; Nepf, 2012).

Different regimes of turbulent flow inside and outside the vegetation area change the shear stress and the transport rate of suspended sediment (López and García, 1998; Houwing, 1999). The bottom shear stress plays an important role in fine sediment movement and the morphology of bed form (Venier et al., 2012). It

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has been reported that plants can cause the increase of the shear stress of the bottom of the tidal flat or the reduction of vertical shear (Leonard et al., 2002) and the resuspension of bottom sediment (Widdows et al., 2008). Normally, the vertical distribution of sediment transport in tidal flow can be described by the Rouse formula, but the sediment process may be different from various tidal types (Shi et al., 2000; Leonard and Reed, 2002). Suspended sediment movement (especially clay and silt) is closely related to hydrodynamic conditions (Kularatne and Pattiaratchi, 2008; Alsina Cáceres, 2011). Recent studies with flume experiments, in which the d_{50} (the diameter of the bed particles at which 50 percent are smaller) was equal to 0.0144 mm, have demonstrated that aquatic ferns can impact sediment turbidity (Wang et al., 2010), and submerged vegetation arrangements may alter sediment trapping and the transport rate of the bed load (Montakhab and Yusuf, 2011). Field observations have demonstrated that loss of the sea grass bed contributes to erosion (Thompson et al., 2004). Yang et al. (2008) stated that the salt marsh plants primarily deposit fine sediment in the following three ways: adherence of suspended sediments onto plants, indirect effects of attenuation of hydrodynamic and prevention of re-suspension. Moreover, sand-trapping in high-turbidity conditions has also been observed (Li and Yang, 2009) and is closely related to plant characteristics, seasonality and weather conditions (Yuan et al., 2008; Coulombier et al., 2012). It is worth noting that most of the above studies were conducted under natural complex conditions. The results of quantitative trapping need to be explored under the combined action of various hydrodynamic and plant characteristics, such as the flow velocity, grain size of sediment particles, turbidity, shoot density of vegetation, relative depth and flexibility (Afzalimehr et al., 2011; Lacy and Wyllie-Echeverria, 2011).

According to the boundary layer theory, the distribution of Reynolds stress and the model of mixing length can determine the shape of the velocity profile (Prandtl, 1925). Based on the observation, the mixing length of the flow inside the canopy can be reduced by the presence of plants. In addition, the flow tends to become more homogeneous with the increase of the shoot density. Given that the interaction mechanism between turbulence and suspended sediment has not been thoroughly determined (Ha and Maa, 2010), and vegetation makes the interaction mechanism between flow and sediment more complicated, it is highly necessary to thoroughly study the relationship between the velocity profile and the interaction mechanism. Moreover, flume experiments have many advantages when exploring the micromechanics of flow and sediment (Neumeier and Amos, 2006; Sottolichio et al., 2011; Neary et al., 2012). In recent years, several new methods of velocity measurement have been used in flume experiments. For example, Acoustic Doppler Velocimeter (ADV) has been chosen to measure flow velocity, suspended sediment concentration (SSC) and sediment settling velocity (Alsina and Cáceres, 2011) simultaneously. It has been affirmed that the measurement results for settling velocity using ADV are more reliable than other methods (Yuan et al., 2008). Therefore, in this work, high-frequency velocity is measured using ADV, and it is also used to test the accuracy of the mixing length hypothesis in vegetation flow based on the experimental data. Table 1 lists the standard mixing length hypothesis and a number of modifications in different applications. Theoretically, the mixing length in flow of tidal flat may be determined both by vegetation and sediment characteristics, but this conclusion is deduced from observations and needs to be further confirmed. Therefore, it is meaningful to explore the application of standard two-dimensional turbulent flow equations, which are described as Eq. (1) and Eq. (2) in turbid flow with vegetation.

$$\mu d^2u \Big/ dz^2 + d\tau'_{xz}/dz = 0 \tag{1}$$

$$\tau'_{xz} = -\rho\overline{u'w'} = \rho l^2(du/dz)^2 \tag{2}$$

in which ρ is the density of flow; μ is the dynamic coefficient of viscosity; u and w are the flow velocities in stream-wise direction and vertical direction, respectively; z is the distance away from bottom in vertical direction; τ'_{xz} is the Reynolds stress, and l is mixing length.

The velocity close to the bottom is important to estimate the effects of vegetation on the sediment transport, such as erosion, deposition, and bed evolution. In addition, the velocity near the boundary determines the flux through the canopy. Considering the prediction of velocity inside the canopy is important in practical applications, it is significant to find a simple method to estimate. The contents of this study aim to investigate and relate the velocity profile to flow turbulence using boundary layer theory. The specific objectives are as follows: (1) obtaining the velocity profiles and turbulence characteristics from experiments, especially the Reynolds shear stress distribution; (2) obtaining the vertical distribution of sediment concentration; and (3) deriving a new velocity profile equation based on the measured Reynolds stress distribution and mixing length model.

2. Methodology

The experiments were performed in a circulation system located at the State Key Laboratory of Estuarine and Coastal Research, East China Normal University, China. The flume was 0.50 m in width, 0.70 m in depth and 33.0 m in length. The water was driven by a pump capable of providing a flow discharge up to 83.3 L s^{-1}. There was a tank for storing the water with a blender that could uniformly stir and mix the sediment. Fresh water was first pumped from the tank into an overflow tower and then passed through pipes to a baffle to suppress the flow fluctuation before it entered the flume. The distance from baffle to test section was 14.4 m. The test section was located in the middle of the flume, where the flow was in a fully developed and uniform turbulent regime. At the outlet of the flume, a tailgate was installed to maintain the flow depth. To prevent the local scour, 0.5 m prior to the test, the section was paved with gravel to form a buffer zone. Before each experiment, the water level was carefully adjusted, and water flowed into the flume for two hours.

All of the experimental runs were designed based on the relative depth, namely, the non-submerged (NS), moderately submerged

Table 1
The mixing length hypothesis and modifications (in which l is the mixing length, z the distance from bottom, and κ the Karman constant).

Names	Equations	Scope of applications
Prandtl (1925)	$l = \kappa z$	Standard 2-D boundary layer
Henderson (1966)	$l = \kappa z(1 - z/H)^{1/2}$	Modification for 2-D open-channel flow, in which H is flow depth
Van Driest (1956)	$l = \kappa z[1 - \exp(-z^+/A^+)]$	Modification for viscous sublayer, in which A^+ is a coefficient of 26.
Huai et al. (2009)	$l = \kappa z(h - h_v)/h(\tau/\tau_{\max})^{1/2}$	Modification for vegetation flow where h_v is vegetation height, h is the flow depth, and τ is the shear stress.