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Short communication

Turbulence structure and flow field of shallow water with a submerged *eel grass* patch

Cui-chao Pang[a,b,c,*], Di Wu[a,d], Xi-jun Lai[a], Shi-qiang Wu[c], Fang-fang Wang[c]

[a] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography & Limnology, CAS, Nanjing 210008, PR China
[b] Changjiang Institute of Survey, Planning, Design and Research, Shanghai Department, Shanghai 200439, PR China
[c] Hydraulic Engineering Department, Nanjing Hydraulic Research Institute, Nanjing 210029, PR China
[d] Hohai University, Nanjing 210098>, PR China

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ABSTRACT

A flume experiment was conducted to investigate the effect of the aquatic herbaceous plant patch on the turbulent structure and flow field of shallow water. The *eel grass* that is widely distributed in the shallow lakes in China was chosen as the targeted plant. The plants were settled in patch form with three groups of densities and flow velocities. The three-dimensional instantaneous velocities were measured using an Audio Doppler Velocitimeter (ADV). The results indicate that the vertical velocity profile in the plant patch exhibits an S-shape from the canopy to the root of the *eel grass*. A secondary maximum in the vertical profile of velocity near the plant root is observed. The turbulent intensity increases from the water surface to the canopy, then decreases to the plant root; there is an inflection point around canopy, where the turbulent intensity deceases from the inner region to the side boundary of the patch. The vertical profiles of the *eel grass* resistance coefficient C_P have different forms at different positions in the patch in general, but the forms of the C_P profiles are similar along the boundary of the patch, and the forms of the C_P profiles are similar in the inner part of the patch. In the patch area, the turbulent flow corresponds to the Quadrant 2 event (ejection event) above the canopy, the turbulent flow corresponds to the Quadrant 4 event (sweep event) below the canopy, but near the bed the Quadrant 1 event (outward interaction), the Quadrant 2 event and the Quadrant 4 event coexist. In the lateral boundary area of the patch the Quadrant 2 event and the Quadrant 3 event (inward interaction event) coexist due to presence of a strong shear layer.

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1. Introduction

In large water bodies with dense herbaceous plants, water is usually clear and low, and a concentration of suspended sediment is observed. The nutrients are apparently lower in the area with dense herbaceous plants than in the surrounding water area without vegetation. The eutrophication degree of water in the herbaceous type lake is found to be lower than that in the non-herbaceous type lake in general. The mechanism of this specific environmental and ecological effect of the aquatic herbaceous plant patch of the lake has not been explained thoroughly. Therefore, it is necessary to promote the study of the effect of natural aquatic herbaceous plants on the turbulent flow structure to explain the environmental and ecological effects of aquatic herbaceous plants and to understand the relevant mechanism of the formation of clean water in the plant patch area and surrounding water.

The experimental study on the effect of aquatic plants on the flow from the resistance aspect began in the 1950s (Abood et al., 2006; Chen, 1976; Chow, 1959; Fathi-Maghadam and Kouwen, 1997; Kris Bal et al., 2013; Kouwen et al., 1981; Larsen et al., 2009; Lee et al., 2004; López and Garcia, 1997; Nepf, 1999; Temple et al., 1987; Velasco et al., 2001; Wang, 2009; Wang and Wang, 2010), which involved the analysis of the effect on the resistance coefficient C_D, the Manning roughness coefficient n, and the Darcy–Weisbach roughness coefficient f. The Manning roughness coefficient n is commonly used in ecological systems and has been studied most thoroughly. The researchers normally thought that the factors affecting the resistance are the shape, flexibility, spatial distribution and density, relative submergence of the plants and Reynolds number of the flow. Chow (1959) indicated that plants

* Corresponding author at: Nanjing Institute of Geography & Limnology, State Key Laboratory of Lake Science and Environment, No.225, Beijing Donglu Road, Nanjing 210008, PR China. Tel.: +86 15850589312.
E-mail address: pangcuichao@163.com (C.-c. Pang).

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have a significant effect on the flow only if the water depth is smaller than a certain value and that the value of n would approach a constant value if the water is of sufficient depth. López and Garcia (2001) found that resistance to flow increases with the increase of the plant density. Chen (1976) studied the resistance in the shallow water flow with natural grass cover on the bed; in this study, *Kentucky Blue grass* and *Bermuda grass* were used in the experiments. Chen (1976) obtained a curve relating the Darcy–Weisbach roughness coefficient with the Reynolds number f–Re, which revealed that f is directly proportional to the bed slope to the power 0.662 and is inversely proportional to the Reynolds number. With the development of measuring instruments, the fine structure of the turbulent flow containing aquatic plants can now be measured. With the data from such measurements, the influences of aquatic plants on the flow field, turbulent structure and substance transportation could be analysed. The analysis results provide the basis for further study of the environmental and ecological changes due to the presence of aquatic plants (Nepf, 1999; Ikeda and Kanazawa, 1996; Kouwen and Li, 1980; Leonard and Croft, 2006; López and Garcia, 2001; Nepf and Vivoni, 2000; Nezu and Onitsuka, 2001; Wang and Wang, 2010; Wilson et al., 2003; Yang and Choi, 2009). Yang and Choi (2009) analysed the characteristics of the flow structure from the aspects of the time-averaged velocity, turbulent intensity and shear stress in the presence of aquatic plants.

In the most of previous research studies, the artificial metal or plastic rigid bar or flexible plastic plant models were used as test aquatic plants in the experiments. Of course, the results from such research do not accurately reflect the effects of natural flexible plants on the flow.

The present research involves an experiment to determine the effects of submerged herbaceous plants on the turbulent structure and flow field in shallow water, such as Lake Taihu, in a relatively wide flume. The *eel grass* that is commonly found in Lake Taihu and other shallow lakes in China was chosen as the test plants. Three main factors were taken into account in the experiment. The first factor is the density of the plants; the second factor is the distribution form of the *eel grass*, with the patch form being selected; the third factor is the flow velocity. Three plant densities and flow velocities were chosen according to an on-site survey in Lake Taihu performed in 2012. The objective of this study is to determine the specific characteristics of the mean and turbulent structure of the flow influenced by an *eel grass* patch, i.e., the quantitative resistance coefficient of *eel grass*, to explain the mechanism of the low turbidity and small pollutant concentration that appears in natural herbaceous plant patches and to provide the basic data for relevant numerical modelling research.

2. Experimental facility and experimental conditions

2.1. Test flume and test plant material

The test flume has a length of 12.0 m, width of 2.0 m and bed slope of 3‰. The test flume has a self-contained water circulation system. The *eel grass* was selected as the test plant. The physical properties of *eel grass* are as follows: the length of the *eel grass* is 32–35 cm; there are eight groups of foliage per plant, which grow directly from the root, and the average width of the foliage is approximately 0.8 cm. The test *eel grass* was replaced every day for each run to keep the *eel grass* fresh and to ensure the physical properties are consistent among all of the runs. The *eel grass* was fixed onto a wire net of size of 4 m × 2 m. The *eel grass* was arranged in quincunx form. The three plant densities used are 172 plants/m^2 (A layout), 86 plants/m^2 (B layout) and 43 plants/m^2 (C layout).

A total of 21 measuring vertical lines were arranged, each of which had 17 measuring points. An ADV (Vectrino+, version 1.03 Beta 4, NORTEK, Norway) was used to measuring the three dimensional instantaneous velocities; the sampling frequency was 25 Hz, and the measuring time was 2 min.

2.2. Experimental conditions

The water depth of flume was 40 cm. The experimental conditions are listed in Table 1.

3. Results and discussions

3.1. Mean flow field

Here, the data from run 8 are discussed as a representative example. The variations of the vertical profiles of u, (u is time-average velocity in x-direction) in the x-direction are shown in Fig. 1a. In the figure, the meaning of label '10B1#2' is as follows: '10' indicates that the test velocity is 10 cm/s; 'B' indicates that the plant density is that of the B layout; '1' indicates the first measuring cross-section; '#2' indicates the second measuring vertical line on the first measuring cross-section. 'KB' in '10KB1#2' indicates that the measurement was performed in a run without a plant patch in the water. Fig. 1a shows that the plants begin to influence the flow at the upstream facet edge of the plant patch (10B1#2) when the flow enters the plant patch: the velocity of the upper water layer above the plant canopy increases and the velocity of lower water layer below plant canopy decreases. Further into the plant patch, the velocity of the lower water layer below the plant canopy reduces sharply and also further decreases along the way downstream (10B2#2, 10B3#2, 10B4#2); the vertical velocity profiles do not recover to the normal pattern because the influence of the plants remains for a certain distance from the downstream edge of the plant patch (10B5#2, 0.5 m from the downstream edge of the plant patch).

3.2. Turbulent structures

Only the results of turbulent intensity are presented here. The turbulent intensity in the plant patch, here denoted as the relative turbulent intensity, $\sqrt{\overline{u'^2}}/\bar{u}$, is discussed. $\bar{u}$ is the cross-section averaged value of u. The variations of vertical profiles of the relative turbulent intensity along the x-direction are shown in Fig. 1b. In general, the turbulent intensity initially increases from the water surface to the plant canopy, then decreases from the plant canopy to the plant root. There is a turning point at the canopy. The turbulent intensity is the strongest around the canopy, as the magnitude of the foliage swinging is the largest and most furious, and the strongest shearing occurs there. The plant density has no effect on the turning point. At the water surface, the turbulent intensity is weak if there are no disturbances from the outside; hence, there are no additional turbulence productions. Near the plant stem base, there is little production of turbulence because the plant stem is fixed there and because the fixed stem base has an apparent inhibition effect on the turbulence transferred from the canopy, with the dissipation of turbulence being greatly strengthened at the plant stem base; hence, the value of the turbulent intensity is even less than the values of the non-plant cases, as seen in comparing the two curves labelled '10B3#2' and '10KB3#2' in Fig. 1b. The vertical profiles approach more or less normal patterns at the location of the outer portion of upstream boundary of the patch (10B1#2) and the place outside of the downstream boundary of the patch (10B5#2),

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