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Hydrodynamics and Contaminant Transportation Development in Vegetated Open Channel

Changjun Zhu and Wenlong Hao
College of Urban Construction, Hebei University of Engineering, Handan, 056038, China

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ABSTRACT

Recently, the construction of ecological civilization has been paid more and more attention. The construction of ecological river offers a new effective and ecological environmental method for river management and planning. Riparian vegetation can conserve soil and water and purify water quality. It also has a good repair for the ecological system. However, vegetation will recede the watercourse's capability of flood discharge. So, it is more important to study the effect of vegetation on flow characteristics. On the base of the former study, the localization is summarized, and the direction of future is drawn.

INTRODUCTION

With the development of industry and agriculture and the rapid growth of the population, more and more pollutants are released into the environment by people. Water resources have been damaged and are becoming scarcer. Water resources, the most precious natural resources for human's survival and development, are one of the basic conditions which support sustainable development. Therefore, protecting and making use of water resources reasonably are particularly important.

Water resources is the blood of nature environment and the river is the important carrier of them. If water resources can not be used and treated reasonably, it will not only cause the waste of water resources, but also may result in water environment and other environmental damage, and even a threat to the safety of human life and property. The construction of ecological watercourse puts forward the new concept of the development of a river and offers a new effective, environmental protection, green and harmless method for river management and planning.

Vegetated river is a part of ecological river. Riparian vegetation can conserve soil and water and purify water quality; it also has a good repair for the ecological system. But there are still many problems. The vegetation not only increase the resistance and enlarge water level, but also reduce the average velocity of water, which reduce the discharging capacity of rivers. Therefore, to discuss the interaction and to understand the action mechanism between water and vegetation have important significance for the construction of ecological river. Recently, the construction of ecological river has been paid more and more attention, and researching on vegetated river has important economic and social benefits.

THE RESEARCH STATUS OF VEGETATED CHANNEL

Vegetated channel is an issue that involves many academic fields, such as vegetation, river, sediment, topography, river evolution, soil erosion and ecological environment and so on. The influence on the flow is complicated and special, and the species of vegetation are varied and the shapes of river section are different. It is the complexity of vegetated channel that brings many difficulties to this study. So research on vegetated channel is fairly inefficient at home and abroad. Since the end of 1980s, increasing number of scientific workers are involved in the research, which makes people to have a further understanding of flow characteristics and the field of vegetated channel, which can be seen in Fig. 1.

The research on the effect of vegetation on water: At present, the domestic study on vegetated channel is still in the initial stage. Huang Ben Sheng et al. (1999) studied the flow capacity of river network in Pearl Delta and hydraulic characteristics on floodplains. The results show that resistance mainly comes from the anti-water area and the influence of resistance of tree and its interaction on the floodplain. The advantages and disadvantages of planting trees on beaches and impact on the flood discharge should be depending on the specific situation.

Later, Wang (2008) conducted a preliminary study on the effect of flexible vegetation channels on flow resistance.

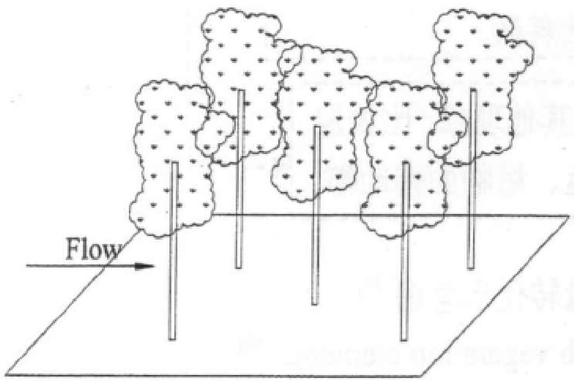

Fig.1: The sketch of rigid vegetation.

Research results show that the existence of vegetation increases the flow resistance significantly. When vegetation is under the status of non submersion, the flow resistance increases with increasing water depth. When vegetation has been just submerged, the flow resistance tends to increase to offset the increase of hydraulic radius or depth of water, and then with the increase of the water depth, the flow resistance will decrease.

Recently, Han Lu (2006) conducted an experiment on water flow full of flexible vegetation on compound channel and analysed the law of flow resistance under the condition of submerged flow. Based on balance equation of force, the resistance formula of submerged vegetation in the floodplain of the waterway with a compound section is deduced as follows.

$$n = \frac{Z^{1/2} R^{2/3} \sqrt{C'_D}}{\sqrt{2gh}} \quad ...(1)$$

Where, C'_D is resistance coefficient and Z is vegetation depth. And then after putting the experimental date into the formula, a relationship curve is obtained that is the resistance coefficient n along the vertical variation and contrasted the curve of resistance coefficient n in Manning formula. It was found that two curves are accordant with each other.

River plants increased water flow resistance and the river roughness. Determining roughness coefficient of vegetated channel effectively is of great significance to calculate the flood discharge capacity correctly and the scientific distribution of vegetation. Shi Bing et al. (2009) simulate nature flexible vegetation with coarse feathers and made the vegetation staggered distributed in the beaches and observe instantaneous velocity of each measuring point using ADV. Using dynamic water pressure and plant flexible deformation, they established a theory formula of calculating the roughness coefficient n in submerged environment as follows.

$$n = \frac{3136}{225} \cdot \left(\frac{5z_0 + 3h_p}{a\pi E d_0^4}\right)^2 \cdot \frac{R_f^2}{V} \cdot \left(1 - \frac{z_0}{h_p}\right)^{-4} \sqrt{S} h_p^{2/3} \quad ...(2)$$

Where S = slop gradient, V = velocity, R_f is individual plant resistance, h_p is plant bending height, E = elastic mould quantity of plant. And additional roughness formula is established on this basis.

$$\Delta n = k_f \left(\frac{z_0}{h_p}\right)^{-4} \cdot \sqrt{S} \left(\frac{h_p}{H}\right)^{2/3} \quad ...(3)$$

Where, k_f is a coefficient related to plant layout and type, and flow conditions. By this, we can analyse and evaluate the effect of river plants on river channel.

In order to determine Manning roughness coefficient of vegetated channel, Tang Hongwu et al. (2003) proposed the concept of equivalent Manning roughness coefficient n_e and established the calculation formula by the equivalent principle of flow resistance.

$$n_e = \frac{1}{U} \left(\frac{B\alpha^{5/2}}{2\alpha + B/H}\right)^{2/3} J^{1/2} \quad ...(4)$$

Where, U is section mean velocity, B is river width, H is water depth, α is closely related to vegetation density, J = energy slope. Thus, it can been seen that equivalent Manning roughness coefficient is a function of section mean velocity, gradient ratio, river width, water depth, plant spacing and plant volume. Based on this, following formula is established.

$$n_e = \left(n_{av}^{3/2} \frac{P_{ew}}{P_e} + n_{eb}^{3/2} \frac{P_{eb}}{P_e}\right)^{3/2} \text{ and } n_{ev}^2 = n_{eb}^2 - n_b^2 \quad ...(5)$$

Where, n_{eb} is equivalent bed roughness, n_b is bed roughness of original section, thus, additional Manning coefficient n_{ev} caused by vegetation is determined. In the experiment, they used rigid cylinders and the Manning coefficient of vegetation is calculated and compared in the submerged and non-submerged conditions. Experimental results verified the theoretical analysis on the discriminant parameter and roughness calculated by water depth can express additional resistance caused by vegetation. The calculation formula of equivalent Manning roughness coefficient contains the physical characteristics of vegetation. So it has general application value and can be used to calculate the roughness in the practical engineering.

Recently, Ding Rui et al. (2012) simulated the effect of submerged plants on water flow by plastic grass in a trapezoidal flat water tank. The result shows that the resistance effect of submerged vegetation on flow is grater if velocity and relative height of plant is larger in the channel with submerged vegetation. There is a boundary in vertical velocity distribution curve. In the upper part of the boundary, the velocity increases, and in the bottom, the velocity decreases. Velocity boundary is above plant canopy or near the relative depth $h/H = 0.3$. The effect of whether two strains of plant leaves having overlaps is different. It will increase flow resistance if they have overlaps. Under the boundary, the flow velocity decreases greatly.

The research on vegetated channel started earlier abroad. In 1926, in order to ensure the flood discharge capacity, the United States had begun to study flow resistance characteristics of vegetated channel. They noted that the resistance characteristic of vegetation is related to water depth and growth of plants. And a large number of laboratory and field experiments are done to study the effect of height, density and stiffness of plant on drag coefficient and Manning roughness coefficient (1981).

Using the cylinder wooden pier instead of trees, Hsieh (1964), Li & Shen (1973) studied the effect of timber pier on flow resistance in the rectangular channel. The experimental results showed that the change of flow velocity is affected by density and arrangement of plants. In addition, using the different round bar instead of plants, Dunn et al. (1996) studied the effect of plants on flow resistance. The results further showed that flow resistance is increased corresponded with the density of plants.

In a very long time, having the vegetation as rigid body, scientists made a large number of experiments. However, little attention has been paid to flexible vegetation. Fathi-Maghadam & Kouwen (1997) pointed out that it will lead to a big mistake of the relationship between velocity and resistance if vegetation is regarded as rigid. Cook and Compbell also pointed out that plant will be bent and swing along the flow direction when water flows through the flexible plants. Reew & Palmer (1949) studied the effect of flexible vegetation on water flow. When plant is bent, it is very regular and roughness of boundary will be decreased. Therefore, water flowing through the flexible plants is actually a moving boundary problem. And flexibility of water and plants is a main parameter on the flow resistance. Fisher (1996) also further pointed out that the resistance of plants to water is related to the type, height, flexibility, density, anti-water area and distribution of plants.

Wang (2003) analysed the experimental date of vegetation in open channel and pointed out that turbulence intensity will be increased significantly with the increasing number of plants. And turbulence intensity will be increased with increasing Reynolds number in the condition of certain density of plants.

Variation of turbulence intensity before and after planting *Eichhornia crassipes* in the watercourse is analysed based on laboratory experiments by Zhu Hong Jun & Zhao Zhen Xing (2007). The experimental result shows, 1. The turbulence intensity of *Eichhornia crassipes* in ecological watercourse is unsteady significantly, 2. The relative turbulence intensity is the largest and its effect on turbulence intensity is the most significant when relative water depth $Y > 0.8$, $0.5 < Y < 0.8$ takes second place and $Y < 0.5$ takes third place, 3. The effect of *Eichhornia crassipes* on water flow is additive and variation of relative turbulence intensity is different in the direction of flow, 4. The distribution of relative turbulence intensity is different by the effect of *Eichhornia crassipes* at the different vertical of same section.

Han Lu (2006) experimented on flow characteristics of flexible vegetation channel and found out that the flow in the floodplain became more irregular and turbulence intensity increased gradually from the bottom to the top of the channel after vegetation is planted in the floodplain. The turbulence intensity reaches the maximum near the surface. And it is found that there are some similarities in turbulence intensity of the same testing point in every direction, namely vertical variation is almost the same, by the experiment. The turbulence intensity of flow in the floodplain reaches the maximum in the front part of vegetation area and decreased gradually. It is found that the turbulence intensity of canopy when vegetation is not fully submerged is larger than it when vegetation is fully submerged by changing the flow. The reason is that the lodge of vegetation is more apparent and the turbulent effect of vegetation canopy on flow becomes smaller gradually when flow becomes larger. However, vegetation swings under the influence of flow and turbulence intensity is increased gradually when the flow is small. The function of channel is the most severe place of flow mixing in compound channel and its turbulence intensity is very large.

Better understanding of Reynolds stress of vegetated channel will help us to understand flow structure. Wang (2003) studied the change of flexible vegetation on Reynolds stress. Research results show that Reynolds stress arrived at the peak value at the top of vegetation canopy, but it decreased rapidly from the top of vegetation canopy. And it decreased slowly from the relative height $z/k = 0.6$.

The aquatic plants change the flow structure of the original river and influence flow characteristics. Variation of time average velocity and Reynolds stress before and after planting *Eichhornia crassipes* in the water course is analysed based on laboratory experiments by Zhu Hong Jun & Zhao

Zhen Xing (2007). The experimental result shows, 1. The longitudinal mean velocity decreases, but horizontal and vertical velocity increases slightly and Reynolds stress of three directions increases when relative water depth Y > 0.8. The longitudinal Reynolds stress increases about 20% when relative water depth 0.5 < Y < 0.8. Changes of Reynolds stress is very small when relative water depth Y < 0.5, 2. The distribution of time average velocity and Reynolds stress are different in the same section of different vertical and in the different sections along the river, 3. The effect of different ways and density of planting *Eichhornia crassipes* on water flow and Reynolds stress are also different.

After vegetation is planted in the floodplain, the regulation of Reynolds stress is changed essentially. According to the research of Rajartnam & Ahmadi (1981), the maximum Reynolds stress should be near the area of junction of channel. However, the maximum Reynolds stress appears in the most severe place of vegetation disturbance after vegetation is planted in the floodplain. According to the analysis of the measured data, Han Lu (2006) did an experiment on the flow characteristics of flexible vegetation channel and found that the maximum Reynolds stress appears in the middle of the floodplain. The most severe place of changes of compound channel flow is in the area of junction of channel where its Reynolds stress is large. Analysis on Reynolds stress along the river finds out that the regulation of Reynolds stress of junction of channel and main channel are opposite. The Reynolds stress is increasing along the river, and this phenomenon is mainly affected by flow coming into main channel and flow shear brought about by lateral and longitudinal movement of flow.

The numerical simulation study on vegetated channel: Su Xiaohui et al. (2003) studied the turbulent flow of vegetated channel for shallow water problems. They built a large eddy simulation turbulence model (k-l LES) of shallow water problems and analysed the mechanism of turbulent flow in vegetated channel. The model compares the simulation results with testing results and verifies the correctness of the model results. This model, which provides a method for the study of turbulent motion mechanism, especially for the development of large scale vortex turbulence, not only can simulate the development and change of flow along the water depth, but also can describe the hydrodynamic behaviour of turbulent flow in vegetated channel.

Using N-S equation, Cheng (2002) derived the two-dimensional flow equation of simulating wide-shallow water along the depth integrated and the equation is discreted by the finite element method in spatial domain. He established a numerical two-dimensional river flow model based on finite element method. By analysing the results, she studied the influence of trees on flow from multiple angles and made a concrete analysis on the influence of plants on river flow field, velocity distribution in open channel, flood discharge capacity and river water level and so on. The physical model test results show that results of computation agree well with previous experimental data. Using numerical two-dimensional model to simulate the flow is feasible and practically acceptable.

Abroad, using three-dimensional algebraic stress model (ASM), Noat et al. (1996) studied hydraulic characteristic of compound channel flow and continuity equation, turbulent kinetic energy equation, and momentum equations are simultaneous solved. However, the three-dimensional algebraic stress model cannot simulate the large scale vortex structure and cannot reflect the turbulent motion of different geometry channel.

Subsequently, using large eddy simulation, Nadaoka & Yagi (1998) proposed a two-dimension diving model which is integrated along the water depth. The application of this model in simulating the shallow water and non-submerged vegetation obtained better results. But, if the river is deep and vegetation is submerged, this model is not applicable. From that, this model also has some defects and limitations. Using the large eddy model, flow problem of wide and shallow rectangular channel has been solved with unilateral and bilateral pile group. Through numerical calculation, the distribution of velocity along the cross-section is consistent with the experimental results.

Effect of vegetation on pollutant transport and dispersion: Based on k-ε turbulence model in the three dimensional non-orthogonal curvilinear coordinate system, Zhu Lanyan (2008) established a three-dimensional model of channel flow under the action of rigid vegetation and transport and diffusion of contaminants. And she studied and analysed the influence of vegetation on pollutant transport on the application of plant in the river. Under the action of submerged vegetation, the vertical diffusion and longitudinal transportation of pollutant are all increased, the vertical distribution of concentration tends to uniform, the vertical mixing section of pollutant is shorten, the initial dilution process becomes faster and the pollution on the downstream is controlled effectively. The matters in water are stranded by the vegetation layer and water pollution degree is lighten.

Using PVC to simulate the flexible plant and glass rod to simulate the rigid plant in the laboratory, a flume experiment on pollutant was carried out and the changing regularity of longitudinal coefficient and lateral dispersion coefficient of pollutants was analysed in the different experimental conditions by workers. The experimental results show that when the other conditions remain unchanged, the vertical diffusion coefficient and the lateral dispersion coefficient increased significantly with the increase of the relative depth in vegetated channel. Effect of plant on the diffusion of contaminants in staggered arrangement was more stable than in aligned arrangement. With the increase of planting density, the lateral diffusion coefficient also increases, but the longitudinal dispersion coefficient will decrease.

Nepf et al. (1997) established the diffusion model of passive scalar in emergent vegetation conditions and they think that the macrophyte turbulence is mainly composed of the wake generated plant. This model can predict the effect of wake on stable diffusion better. But as the wake percentage is difficult to determine, it still has limitations in practical application. In view of this, Nepf et al. (1997) made a further study on the diffusion coefficient under different Reynolds number. The results show that the diffusion of emergent aquatic plant is mainly determined by the following factors together, 1. The turbulence diffusion caused by plant plume, 2. The physical barrier of plant change the transport of pollutants and mechanical diffusion is formed. When the Reynolds number is large, turbulent diffusion plays a main role. However, with the increase of plant density and the decrease of the Reynolds number, mechanical diffusion will play a major role. Considering the turbulent diffusion and mechanical diffusion, the diffusion model of pollutants was established. In order to study the effect of plants on the longitudinal dispersion, Nepf et al. (1997) experimented with rhodamine as the tracer. The experimental results show that the vertical shear is weakened, flow turbulence and vertical diffusion is strengthened, which weakened the longitudinal dispersion due to the presence of plants. The 'dead zone' of the rear part of plant improved the longitudinal dispersion to some extent. Moreover, only when the plant density is large, mechanical dispersion induced by plant plays an important role in the overall longitudinal dispersion. Tanino & Nepf (2008, 2009) studied the lateral dispersion of plants of different Reynolds number and found the relationship between Reynolds number and volume fraction and lateral dispersion coefficient of plants. And transverse dispersion model of plants is established and the reliability of the model is demonstrated by tests.

CONCLUSION AND PROSPECTS

To sum up, some research and the theoretical achievements at home and abroad are summarized, and the research on the vegetated channel is still at the initial stage and need deeper research. Now some opinions and suggestions on the previous research and development in the future are put forward:

1. The past researches on vegetated channel mainly focus on the effect of flexible and rigid vegetation in plant height, density and arrangement on the turbulent characteristics, flow velocity, Reynolds stress and the roughness coefficient and so on, but these studies are only limited to qualitative, and more research is needed in the quantitative assessment.
2. The model established by the effect of the existence of vegetation on the channel just stay in the ideal assumptions, and there are still some defects and limitations in the practical application and need to be further improved and perfected.
3. So far, the experimental study on the flow characteristics of vegetation has been limited to straight channel, which do not consider the effect of the change of section shape on the water. Therefore, the study on the flow characteristics of river need to been strengthened.
4. Most of the experiments are carried out in the sink, because the actual structure is complex, the simulation of the actual river still has certain difficulty, and laboratory mostly use PVC or other materials to simulate plant, which focuses on the simulation of single plant. The effects of varieties and complex shape of vegetation on the river need to be further studied.
5. The pollutant transport law in vegetated channel needs to be further studied in-depth. And the issues related to plant on river ecological system, flood and water treatment should also be given more attention.

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