Experimental Study on Flow Characteristics in a Compound Open Channel with Flexible Vegetation

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Abstract. In order to study the effect of flexible vegetation for the flow in open channels with flood plains, a series of experiments were carried out in a laboratory flume with a two-stage floodplain. Four cases, i.e., dense parallel arrangement, normal parallel arrangement, sparse parallel arrangement and no vegetation condition, were designed with fixed water depth and discharge. By using three dimensional (3D) laser Doppler velocimeter (LDV) and other instruments, under the condition of the four cases, 3D flow velocities, water level and turbulence intensity were measured. The experimental results show that, compared with the non-vegetation situation, the arrangement of grasses on the floodplain will increase the water surface gradient, hydraulic gradient and turbulence intensity to a certain extent.

1. Introduction

Floodplain is an important part of natural rivers, and vegetation widely exists in the floodplain. Aquatic vegetation can affect the original flow structure, including increasing the resistance of the river bed, raising the water level and reducing the flood carrying capacity [1]. However, aquatic vegetation can avoid soil and water loss, improve the water quality and stabilize river banks and protect floodplains [2]. In the compound open channel, due to the obvious energy exchange between floodplains and main channel, the turbulent characteristics of the flow are enhanced, and the flow structure becomes more complex [3].

The research on the flow characteristics in rivers or laboratory flumes with vegetation in the floodplains can provide scientific basis for river ecological restoration, environmental pollution control, flood control engineering, and has a certain practical engineering value [4-7]. As a result, a great deal of research has been carried out on flow characteristics with vegetation, and a lot of research results have been achieved, which includes physical experiments and numerical simulation.

In general, studies of the effect of submerged flexible vegetation on water flow have mainly focused on model vegetation such as wheat, polyethylene film and artificial model plants. Natural flexible vegetation with regular blades has also been reported, such as Myriophyllum and Hydrilla, leafy shrubs, grass, and Sagittaria sagittifolia [8-11]. However, the morphological characteristics of natural...
submerged vegetation, such as leaf size and shape, stem thickness, and flexibility are heterogeneous among different species [12]. The study of the impact of natural submerged flexible vegetation with typical morphological characteristics and ecological value on the physical process of water flow, such as velocity structure and turbulence characteristics, would contribute to the protection and restoration of water ecology.

In terms of physical experiments, Kouwen carried out a series of experiments and found that the flow velocity above the flexible vegetation is logarithmic distribution, and deduced the velocity distribution formula [13]. Petryk used different experimental methods to determine the vegetation resistance coefficient, and determine the relationship between the vegetation projection area and the vegetation resistance coefficient [14]. Knight and Hamed conducted a series of experiments in a compound flume composed of a main channel and two symmetrical floodplains, and analyzed the distribution of boundary shear stress [15].

However, it can be found that the research results of measurements or numerical simulation of flow with flexible vegetation in a flume with two stages of floodplains are still very few, especially use 3D-LDV to measure the velocity and turbulence intensity. In this paper, the water flow with flexible vegetation (artificial model grass) on the floodplain in a compound open channel with two-stage floodplain was measured by using 3D-LDV. Under the condition of certain water depth and discharge, the influence of different arrangement modes of flexible vegetation on the water flow structure is studied.

2. Experimental Method

2.1. Measured Instruments and Equipment

The experiment is carried out in a glass flume with 15m long, 0.49m wide and 0.5m deep. The main channel occupies the left half of the channel and its width is 0.24m, while the two stages of floodplain are arranged at the right half of the channel. The bed of the main channel and the flood plains is composed of aluminum alloy. Both the width and height of the first and second floodplain are 0.125m. The flume has a fixed bottom slope (slope of 0.1%), and is consisted of three parts: intake tower, glass flume, and circulating pool. Figure 1 is the flume and measured instruments.

![Figure 1. Flume and measuring instruments.](image)

The 3D-LDV produced by TSI company is used to measure the 3D flow velocities. The sampling time of each measuring point is set as 30s. The relative measurement error is less than 1%. The water level is measured by the water level probe, and the flow discharge is automatically read by an electromagnetic flowmeter. Figure 2 shows the cross section of the flume.
2.2. Experiment Conditions and Measuring Points Layout

2.2.1. Model Material. Plastic grass was used to replace the aquatic flexible vegetation, with a height of 0.08m. Each plant is composed of three branches, and each of the branches has 12 leaves. The diameters of the trunk and canopy of the grass are 0.008m and 0.03m, respectively. Figure 3 shows the model grass used in the experiments.

![Model grass used in the experiments.](image)

Figure 3. Model grass used in the experiments.

2.2.2. Position of Measured Points. As shown by table 1, four cases are designed based on the density of the model grasses. In the first three cases (Cases 1-3), model grasses are evenly placed on the vegetation area. The transverse distances between two grasses are 0.05m for all of the three cases. And longitudinal distances of two neighbor grasses are 0.05m, 0.10m and 0.20m, respectively. In order to compare the effect of the grasses to the water flow, Case 4 is designed with the condition without any grass in the flume. The vegetation area was arranged at 7.81-8.77m away from the water inlet, and its length was 0.96m. The model grasses are arranged in parallel on the first stage of the floodplains.

Figure 4 shows the grass arrangement and measured position under the four cases. Ten cross sections are set along the flow direction (x direction). Two measured sections are set before the vegetation area with spacing of 0.3m, and five measured sections are set in the vegetation area with distance of 0.2m. Three measured sections are set after the vegetation area with distance of 0.2m. Nine measured sections are arranged along transverse direction (y direction), and the spacing of five
measured sections in the main channel is set as 0.045m, while it is set as 0.025m for sections in the first stage floodplain. In vertical direction, (z direction), a total of 17 measured sections are set. The first section is 0.015m from the bottom of the flume, of which the interval between the first 7 points is 0.02m, and the other 10 measured points are 0.01m.

![Vegetation arrangement and measured point location under four cases.](image)

**Figure 4.** Vegetation arrangement and measured point location under four cases.

**Table 1.** Basic parameters of four typical cases.

| case | Grass arrangement | Original height of the grasses/m | Effective height of the grasses/m | Discharge /m³/s | Water depth/m |
|------|-------------------|----------------------------------|----------------------------------|-----------------|--------------|
| 1    | dense             | 0.080                            | 0.055                            | 0.0296          | 0.240        |
| 2    | normal            | 0.080                            | 0.051                            | 0.0296          | 0.240        |
| 3    | sparse            | 0.080                            | 0.048                            | 0.0296          | 0.240        |
| 4    | no vegetation     | -                                | -                                | 0.0296          | 0.240        |

3. Experiment Results and Analysis

3.1. Water Level Distribution

When the water flows through the vegetation area, the vegetation will produce resistance to the water flow, and the flow velocity will be reduced accordingly. Therefore, the water level in the upstream of the vegetation area rises, and after the water flows through the vegetation area, the water level drops. As a result, large water surface slope forms in the vegetation area, as shown in figure 5.
Figure 5. Water level distribution along the flow direction.

In figure 5, it can be seen that the grass density has a great influence on the backflow height and water surface gradient. Under the condition of the four cases (Cases1-4), the water level distribution characteristics are similar. In other words, the water level rises slowly in the upstream of vegetation area (6.8m<x<7.81m), and it reaches the highest value at the first row of vegetation (x=7.81), then it drops rapidly in the vegetation area (7.81m<x<8.77m). After leaving the vegetation area (x>8.77m), it shows a slow downward trend. And it also can be found that the water surface gradient increases with the increasing of the vegetation density in the vegetation area.

3.2. The Inclination Angles of the Model Grasses
In this study, the inclination angles of the grasses at three cross sections, which located in the inlet, the central, and the outlet in the vegetation area, respectively, are compared among the four cases, as shown in table 2. When the water flows through the vegetation area, it impacts the flexible grasses and makes the stem of the grasses inclined toward to the downstream. The inclination angle of the stems is related to the grass density when the water discharge and water depth at the outlet of the flume are kept constant. It can be seen that when the water level and discharge are kept constant, the inclination angle of the vegetation increases with the increasing of the grass density. In addition, the inclination angle is smaller at the inlet of the vegetation area, and then it increases along the way. In other words, the influence of the first row of grasses is greater than that of the last row of grasses.

Table 2. Inclination angles of the vegetation under four cases.

| case | Vegetation arrangement | Inclination angle | Discharge /m³/s | Water depth/m |
|------|------------------------|------------------|-----------------|--------------|
|      |                        | inlet            | central         | outlet        |              |
| 1    | dense                  | 37.16            | 41.56           | 50.55        | 0.0296       | 0.24         |
| 2    | normal                 | 35.02            | 39.04           | 48.23        | 0.0296       | 0.24         |
| 3    | sparse                 | 30.85            | 37.16           | 46.81        | 0.0296       | 0.24         |
| 4    | no vegetation         | -                | -               | -            | 0.0296       | 0.24         |

3.3. Distribution of the Flow Velocity

3.3.1. Velocity Distribution along the Transverse Direction. In order to compare the flow velocity among four typical cases, the same horizontal cross section (the distance of the section to the main
channel bed is 0.215m) is chosen. The velocity field on the section of the four cases are presented, as shown in figure 6.

![Figure 6. The studied flume during measurement.](image)

It can be seen from figure 7 that the grasses on the floodplain can affect the flow field not only on the floodplain, but also on the main channel. However, the influence of the flow field on the floodplain is larger than that on the main channel.

![Figure 7. Flow field distribution in a typical horizontal section (z=0.215m).](image)

In order to further analyze the influence of different arrangement of grasses on the flow velocity, 5 lines are chosen on the horizontal section (z=0.215m), as shown by figure 8. The 5 lines are from x1 to x5, in which x2, x3 and x4 are located at the inlet, the central, the outlet of the vegetation area, respectively, while x1 and x5 are located at the upstream and downstream of the vegetation area, and x1 is 0.6m away from the first row of grasses, and x5 is 0.3m away from the last row of the grasses.

In figure 8, x1 and x5 are located in the non-vegetated area, and the velocity along the two rows is relatively uniform. x2, x3 and x4 are located in the vegetated area, the velocity on the floodplain is
staggered for Cases 1, 2 and 3 because of the resistance of vegetation. When there is no vegetation on the floodplain (Case 4), the velocity distributions along the transverse direction are more uniform. Furthermore, because of the resistances of floodplain bed and the drag force of the vegetation, the velocity on the floodplain is smaller than the main channel.

![Velocity distribution along y direction at a typical horizontal section (z = 0.215m)](image)

**Figure 8.** Velocity distribution along y direction at a typical horizontal section (z = 0.215m).

### 3.3.2. Comparison of the Flow Velocities among Four Typical Cases.

In order to further study the influence of floodplain vegetation on flow velocity, a cross section, which is located at x=0.851m from the water inlet, is chosen to compare the flow velocities. Contours of the flow velocities on the section under the conditions from Case 1 to Case 4 are presented, shown in figure 9.

![Contour plots of flow velocities](image)
Figure 9. Contours of the flow velocity on a typical cross section of four cases.

In the main channel, the flow velocity distributions in the main channel are similar for all of the four cases. The flow velocity is small near the bed and banks of the main channel and it is increasing from the bed to the water surface, and arrives its maximum value on the free surface. However, the flow structures are complex in the floodplain and near the junction between the main channel and the floodplain. In Case 4, when no grasses are set in the floodplain, the flow velocity is increasing from the bed of the floodplain to the water surface and obtains its maximum value on the free surface. However, in Cases 1, 2 and 3, when the grasses are placed in the floodplain, the maximum flow velocities can be found below the water surface.

3.3.3. Comparison of the Fluctuating Velocities. In order to research the influence of the grasses to the flow fluctuating velocities in x and y directions, a measured point (P) is chosen to exhibit them. The measured point is placed at the floodplain of the flume at the position that is 0.851m from the inlet, 0.341m from the left bank, and 0.205m from the bed of the studied area in the flume. The variation of the fluctuating velocities (along the x and y directions with time of 30s is shown in figure 10.
Figure 10. Fluctuating velocities in x and y directions at point P of four cases.

It can be seen from figure 10 that in the case of no vegetation (Case 4), the fluctuations of fluctuating velocities in the x and y directions are small. However, the fluctuating amplitudes in the x and y directions become larger and larger with the increasing of the grass density in the flood plain. In other words, the turbulence intensity is smaller if no grasses are set at the floodplain, and the existence of the grass in the floodplain will increase the turbulence intensity.

4. Conclusion
In this study, 3D-LDV is used to measure the 3D flow velocity, water level distribution, water surface slope and other hydraulic characteristics in a compound open channel with flexible vegetation on the first grade floodplain. The influence of vegetation arrangement on the flow is studied and the following conclusions can be obtained.

(1) The arrangement of grasses on the floodplain has a great influence on the water level distribution. The water surface gradient increases with the increasing of the vegetation density.

(2) The inclination angle of the grasses increases with the increasing of the grass density, and the inclination angle is smaller at the inlet of the vegetation area, and then it increases along the longitudinal direction, indicating that the influence of the grasses on the flow is decreasing gradually.

(3) The grasses on the floodplain can affect the flow field not only on the floodplain, but also on the main channel. However, the influence of the flow field on the floodplain is larger than that on the main channel.

(4) Along the transverse direction, the velocity on the floodplain is staggered. When there is no vegetation on the floodplain, the velocity distributions along the transverse direction are more uniform. Furthermore, the velocity on the floodplain is smaller than the main channel.

(5) The flow velocity is small near the bed and banks of the main channel and it is increasing from the bed to the water surface, and arrives its maximum value on the free surface. The flow structures are complex in the floodplain and near the junction between the main channel and the floodplain.

(6) The turbulence intensity is smaller if no grasses are set at the floodplain, and the existence of the grass in the floodplain will increase the turbulence intensity.

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