Research Article

Experimental Study on Flow Velocity Structure and Turbulence Characteristics in Open Channel with Biomimetic Grass

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Received 8 December 2020; Accepted 10 August 2021; Published 17 August 2021

Academic Editor: Qian Fang

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The problem of suspension treatment of oil and gas pipelines has been highly concerned by engineering construction units and researchers. Research shows that the bionic grass can effectively reduce the flow rate, promote sediment deposition, and control the development of the pipeline suspension area. The velocity distribution of open channel flow with bionic grass is very complex. The height and spacing of bionic grass will affect the flow velocity distribution. At present, the flow velocity in open channels containing bionic grass is mainly studied by measuring the velocity variation in the front, middle, and back of bionic grass, but few effective measurements are made for the full velocity field. This paper describes the use of modern means of an advanced test, using standard particle image velocimetry (PIV) measurements with bionic grass along the water channel to the vertical plane of the distribution of the velocity field. The probability density distribution, spatial correlation of pulsating velocity, turbulence intensity, Reynolds stress, and turbulent kinetic energy in the open channel after the protection section of bionic grass were further analyzed.

1. Introduction

Bionic grass is based on the principle of marine bionics. It is processed with a new type of polymer material which is resistant to seawater immersion and long-term erosion [1]. Studies at home and abroad have shown that bionic grass can not only effectively reduce the flow velocity and promote sediment deposition but also will not produce secondary environmental pollution [2, 3], which is mainly used for the protection of underwater suspended pipelines. At present, there are few results of physical model experiments on bionic grass, mainly discussing the variation law of flow velocity in the front, middle, and back of bionic grass and the change of sediment deposition in the protective section of bionic grass [4]. It is rare to effectively measure and study the full field velocity of the open channel flow with the bionic grass protection section, but the flow velocity distribution in the channel containing bionic grass is the basis for the further study of the transport law of mud, sand, and matter in the flow.

Lu et al. [5] observed and analyzed the turbulence mechanism of natural rivers. It is obtained that the probability distribution of pulsating velocity is approximately normal in the fully developed free turbulence region, and that is skewed in the strong shear turbulent region near the wall. The turbulence intensity of each vertical line is uniform in the range of relative water depth greater than 0.4, which is approximately linear, reaches the maximum near the bottom of the river, and then decreases rapidly to zero at the bottom of the river. The distributions of Reynolds normal stress and shear stress along the vertical line in the nearshore and the center of the river have similar characteristics; there is also a certain difference. Yang et al. [6] selected plastic straws, duck feathers, and plastic grasses to simulate trees, shrubs, and weeds and pass the flume test. The turbulence characteristics of floodplain flow under the action of different beach plants are discussed: ① the pulsation of water flow has strong randomness and periodicity; ② the fluctuating velocity in the longitudinal, transverse, and vertical directions satisfies the normal distribution; ③ the transverse momentum exchange

is larger than the vertical momentum exchange; ④ different beach plants have different effects on the turbulence intensity of water flow. After planting plants on the beach, the turbulence intensity of the flow is enhanced, and the longitudinal and horizontal turbulence intensity is the same. The longitudinal and transverse turbulence intensity obeys S-shaped distributional. Li et al. [7] studied flexural deformation characteristics of submerged flexible vegetation canopy and its influence on flow resistance characteristics of open channels. The results show that bending deformation of vegetation helps to transfer water flow into deep canopy depth, thereby reducing resistance further. Caroppi et al. [8] experimented flume layout novel; transverse shear layer induced by flexible riparian plants was studied. The structure of the mean flow field and the turbulent flow field is determined by the acoustic Doppler velocity measurement technique, and the results show that the morphology and reconstruction of complex plants have a great influence on shear layer dynamics in some vegetation channels. Lateral momentum transport under leaf surface conditions is more effective than that of simple vegetation shear layer. Chembolu et al. [9] studied the flow characteristics of natural heterogeneous vegetation patches under submerged conditions. The results showed that the velocity reduction efficiency was 10% higher than that of flexible grasses due to other vegetation forms in mixed heterogeneous patches. Plant morphology and canopy porosity play an important role in controlling the position intensity and thickness of active momentum exchange at top of the canopy. In order to study the effect of plant morphology on flow structure, Zhang et al. [10] carried out laboratory experiments on two kinds of submerged flexible vegetation. Laboratory experiments on two kinds of submerged flexible vegetation were carried out. The existence of these two types of vegetation changes the vertical distribution of mean velocity, Reynolds stress, and turbulent kinetic energy. With the decrease of the frontal area of the lower canopy, the adjustment of airflow in the canopy results in an inverse velocity gradient region and a local velocity maximum in the canopy. The Reynolds stress is proportional to the average velocity gradient, which reaches the maximum at the interface of the umbrella surface and shows a negative value in the area where the reverse velocity gradient appears in the umbrella surface.

In this paper, the flume experiment was carried out, and the velocity structure behind the bionic grass protection section was measured and studied by using the particle image velocimeter (PIV). The time-averaged velocity distribution, the pulsating velocity probability density distribution, and the pulsating velocity spatial structure of the open channel flow behind the bionic grass protection section under different working conditions were analyzed, and the influence of the existence of bionic grass on the flow velocity structure was quantitatively expounded.

2. General Situation of Test

In this paper, the physical model test is carried out in a high precision variable slope flume. The trough is 12.6 m long, 0.25 m wide, and 0.25 m high. To reduce the influence of the flume sidewall joint on flow structure, the side and bottom of

the flume are composed of 3.6 m long glass plate, glass installation error is less than ± 0.2 mm, and the structural deformation of the flume is less than ± 0.3 mm. For the convenience of PIV entering the light and taking pictures with the camera, bevel bonding is used between the glass base plate and the sidewall glass. A rectifier grille is placed at the entrance of the sink and a hinged tail door is arranged at the exit. The flume is equipped with an automatic water level and flow control system, an ultrasonic water level meter is used to measure the test water depth, and an electromagnetic flowmeter is used to measure the test flow. The instantaneous flow velocity is measured at a distance of about 0.1 m from the end section of the bionic straw mat, and the distance is 0.08 m, as shown in Figure 1.

Experimental flow is constant flow. The normal model was adopted in experiments, and the velocity in the model is determined according to the gravity similarity criterion, and the test scale is 1/20. Bionic grass used in bionic straw mattress samples was used as engineering samples of T25 type, the actual size of bionic straw mattress is $5 \text{ m} \times 5 \text{ m}$, the spacing between each row of bionic grass in the straw mattress was 1.67 m, and the grass is 1.5 m high. In the experiment, the laying of bionic grass is referenced by practical engineering conditions. At the same time, to analyze the influence of height and laying distance of grass on flow velocity structure, samples of different grass heights and different laying spacing were set up in this experiment, and each operation is divided into 3 parallel samples; test condition parameters are shown in Table 1.

3. Analysis of Experimental Results

3.1. Regularity of Lodging Regularity of Bionic Grass under the Water Flow. The lodging height of the T25 bionic straw mat mattress under different velocity conditions (0.18 m/s, 0.22 m/s, and 0.27 m/s) was measured by experiments, and the results are shown in Table 2. During the test, the lodging status of biomimetic grass is shown in Figure 2. It can be seen from Table 2 that the lodging value of bionic grass increases with the increase of flow velocity. In the case of high flow velocity, bionic grass can form a cover layer on the riverbed by reducing the lodging height to reduce the erosion of water to the riverbed.

3.2. Longitudinal Time-Averaged Velocity Distribution behind the Protective Section of Bionic Grass. Longitudinal time-averaged distribution of flow along the bionic grass protection section is shown in Figure 3. The existence of bionic grass increases resistance to water flow, and the flow through bionic grass changes the original velocity distribution: (1) the flow velocity near the bottom of the canal decreases obviously, and a negative value appears in some areas, resulting in a whirlpool, and with the increase of the average velocity of the cross-section, the velocity near the bottom of the canal is all negative, resulting in large-scale reflux; (2) the longitudinal velocity of flow near bionic grass increased obviously near the lodging position (about 2 cm) (see Table 2) of biomimetic grass. It shows that when the water flows through the bionic grass, the cross-section increases

FIGURE 1: Schematic diagram of the flume test.

TABLE 1: Test conditions and related parameters.

Conditions	Depth, d (m)	Flow, Q (L/s)	Velocity, v (m/s)	Re	Fr	Chezy coefficient, C	Coefficient of motion viscosity, ν ($10^{-6} \text{ m}^2/\text{s}$)	The height of bionic grass, H_g (m)	Arrangement
B25S	0.109	6	0.18	8324.7	0.171	624.065	1.27	0.075	
B25M	0.112	5	0.22	10268.4	0.217	622.568			
B25L	0.090	6	0.27	11040.4	0.285	611.579			

TABLE 2: The lodging of bionic grass under different working conditions.

Conditions	The original height of bionic grass, H_g (cm)	Lodging value (cm)
B25S	7.5	0.5
B25M	7.5	1.0
B25L	7.5	2.0

FIGURE 2: Lodging values of bionic grass at different flow rates. (a) $v = 0.18 \text{ m/s}$. (b) $v = 0.22 \text{ m/s}$. (c) $v = 0.27 \text{ m/s}$.

suddenly, which leads to the sharp fall of the water surface and the water drop; (3) the position away from the bionic grass is near the lodging position of the bionic grass (about 2 cm); the longitudinal velocity of the flow gradually decreases; (4) the flow velocity above the lodging position of the bionic grass is relatively small, and most of them are negative, because when the flow flows through the bionic grass, the lodged grass becomes a new bed surface, which causes the flow to be partially deformed and separated, and the secondary flow that produces rotational motion moves backward with the flow direction.

In order to analyze the vertical velocity distribution of longitudinal velocity under different working conditions, the maximum section $x = 2 \text{ cm}$ was taken from velocity variation, as shown in Figure 4. It can be seen that when the average velocity of the cross-section is small, the longitudinal velocity of the flow in the 2 cm range of the rear canal bottom of the bionic grass section is linear, and the value is close to zero, and above the 2 cm of the canal bottom, the vertical distribution of longitudinal velocity is S-shaped. With the increase of the average velocity of the cross-section, the longitudinal velocity in the 2 cm range of the rear canal

FIGURE 3: The distribution of the time-averaged longitudinal velocity in different working conditions. (a) B25S. (b) B25M. (c) B25L.

FIGURE 4: The vertical distribution of the time-averaged longitudinal velocity in different working conditions ($x = 2$ cm).

bottom of the bionic grass section shows a parabola distribution along with the water depth, and above the 2 cm of the canal bottom, the vertical distribution of longitudinal velocity is similar to S-shaped. The maximum velocity of time-average velocity at vertical longitudinal direction is obtained at $y = 5.4$ cm, $y = 4.9$ cm, and $y = 3$ cm, respectively. Maximum values are 0.235 m/s, 0.30 m/s, and 0.24 m/s, respectively. It can be seen that the position of the maximum longitudinal time-averaged velocity on the vertical line gradually moves downward with the increase of the average velocity of the cross-section, which is related to the lodging of bionic grass.

3.3. Probability Density Distribution of Fluctuating Velocity after Bionic Grass Section. The fluctuating velocity of turbulent flow in the open channel can be expressed by probability density distribution with spatial and temporal variation characteristics to predict the basic characteristics of turbulent motion. This paper studies the probability density of pulsating velocity, calculating the probability of

fluctuating velocity in each working condition, and the probability distribution curves of longitudinal and vertical pulsating velocity are plotted. The “-” sign represents direction. Figure 5 shows the probability density distribution of longitudinal fluctuating velocity in different working conditions. It shows that the probability density of longitudinal fluctuating velocity of flow velocity in open channel is normal distribution after the bionic grass protection section. With the increase of the average velocity of the cross-section, the probability density of the longitudinal fluctuating velocity decreases, the kurtosis coefficient of the normal distribution decreases, and the trend of the peak shape is flatter.

The probability distribution of vertical fluctuating velocity in different working conditions is shown in Figure 6. It can be seen that the vertical fluctuating velocity probability density of the open channel flow behind the bionic grass protection section shows a normal distribution, but compared with the longitudinal fluctuating velocity probability density distribution, the overall peak distribution is steeper, the kurtosis of the normal distribution is larger, and the peak is sharper. When the average velocity of the cross-section is smaller, the probability density of vertical pulsation velocity reaches 62.5%; this shows that when the inflow velocity is low, the fluctuation of the vertical pulsating velocity behind the bionic grass section is small, but with the increase of the average velocity of the cross-section, the probability density of the vertical fluctuating velocity decreases, the kurtosis coefficient decreases, and the overall peak trend tends to be flat.

3.4. Spatial Correlation of Fluctuating Velocity after Bionic Grass Section. Usually, the spatial correlation structure of pulsating velocity can be described quantitatively by the correlation coefficient. The larger the correlation coefficient, the better the spatial correlation of velocity; on the contrary, it will be worse. Spatial correlation of pulsating velocity includes 2 categories of autocorrelation and correlation, C_{uu} and C_{vv} are autocorrelation coefficients, $C_{uu} = (1/n) \sum_{i=1}^n u_i(x_0, y_0)u_i(x_1, y_1)/u'(x_0, y_0)u'(x_1, y_1)$, $C_{vv} = (1/n) \sum_{i=1}^n v_i(x_0, y_0)v_i(x_1, y_1)/v'(x_0, y_0)v'(x_1, y_1)$, C_{uv} and C_{vu} are mutually related numbers, $C_{uv} = (1/n) \sum_{i=1}^n u_i(x_0, y_0)v_i(x_1, y_1)/u'(x_0, y_0)v'(x_1, y_1)$.

FIGURE 5: The probability distribution of longitudinal pulsation velocity in different working conditions. (a) B25S. (b) B25M. (c) B25L.

FIGURE 6: The probability distribution of vertical pulsation velocity in different working conditions. (a) B25S. (b) B25M. (c) B25L.

$y_1)/u'(x_0, y_0)v'(x_1, y_1)$, $C_{vu} = (1/n) \sum_{i=1}^n v_i(x_0, y_0)u_i(x_1, y_1)/v'(x_0, y_0)u'(x_1, y_1)$, (x_0, y_0) and (x_1, y_1) are coordinates of arbitrary two points in space, n is the sample capacity, u is the longitudinal fluctuating velocity and v is the vertical fluctuating velocity, and $u' = \sqrt{(1/n) \sum_{i=1}^n u_i^2}$ and $v' = \sqrt{(1/n) \sum_{i=1}^n v_i^2}$ are longitudinal and vertical turbulent intensities, respectively.

This paper selects the geometric center point of flow field acquisition window as (x_0, y_0) , and the surrounding space point is (x_1, y_1) ; calculating autocorrelation coefficients and correlation numbers, the spatial correlation structure characteristics and variation regularity of flow velocity in an open channel with bionic grass were analyzed.

3.4.1. Spatial Autocorrelation. Figures 7 and 8 show distributions of autocorrelation coefficient C_{uu} and C_{vv} cloud images of flow velocity in open channel flow after bionic grass protection section, respectively. The result shows that C_{uu} and C_{vv} are positively correlated spatial structures around a central point; C_{uu} and C_{vv} values decrease with increasing distance between analytical points and geometric center points of acquisition windows, and the greater the distance between two points, the weaker the spatial autocorrelation of pulsating velocity between them. The innermost circle of C_{uu} and C_{vv} images is roughly rounded; C_{uu} and C_{vv} near circle center are isotropic. Along with the

increasing average velocity of cross-section, the innermost circle of C_{uu} and C_{vv} images is closer to circle. Moreover, the area of the innermost circle increases first and then decreases.

For further quantitative analysis of C_{uu} and C_{vv} cloud images distribution features and to define an area coefficient of $\zeta = A_r/A$, A_r is the area surrounded by isoline corresponding to correlation coefficient r and A is the total area of the analytical window. Obviously, with the bigger ζ , the proportion of area surrounded by isoline of the correlation coefficient is larger than that of the window area. ζ_{uu} , ζ_{vv} , ζ_{uv} , and ζ_{vu} respectively indicate area coefficients of C_{uu} , C_{vv} , C_{uv} , and C_{vu} respectively. Tables 3 and 4 show values for ζ_{uu} and ζ_{vv} under different operating conditions.

As can be seen from Table 3, ζ_{uu} and ζ_{vv} generally increase first and then decrease with r value increasing; when r is larger (larger than 0.02), the more obvious the decreasing changes. It shows that the variation of the area surrounded by isoline is more sensitive when r is larger; when r is at about 0.02, ζ_{uu} and ζ_{vv} values reach maximum. Along with the increasing average velocity of cross-section, the maximum values of ζ_{uu} and ζ_{vv} decreased firstly and then increased.

3.4.2. Spatial Correlation. Figures 9 and 10 show distributions of correlation number C_{uv} and C_{vu} cloud images of the fluctuating velocity of open channel flow after bionic grass protection section, respectively. The result shows that the values of

FIGURE 7: The distribution of C_{uu} in different working conditions. (a) B25S. (b) B25M. (c) B25L. FIGURE 8: The distribution of C_{vv} in different working conditions. (a) B25S. (b) B25M. (c) B25L.TABLE 3: The value of ζ_{uu} and ζ_{vv} in different working conditions.

r	Conditions					
	ζ_{uu}			ζ_{vv}		
	B25S	B25M	B25L	B25S	B25M	B25L
<-0.14	0.000	0.000	0.000	0.000	0.000	0.000
$-0.14\sim-0.1$	0.000	0.000	0.001	0.000	0.000	0.000
$-0.1\sim-0.06$	0.011	0.008	0.037	0.011	0.006	0.008
$-0.06\sim-0.02$	0.080	0.057	0.203	0.136	0.121	0.174
$-0.02\sim0.02$	0.214	0.158	0.352	0.405	0.397	0.506
$0.02\sim0.06$	0.328	0.278	0.255	0.329	0.313	0.271
$0.06\sim0.1$	0.210	0.236	0.113	0.096	0.117	0.037
$0.1\sim0.14$	0.081	0.119	0.029	0.017	0.034	0.003
$0.14\sim0.18$	0.047	0.067	0.004	0.003	0.009	0.001
$0.18\sim0.22$	0.021	0.041	0.002	0.001	0.002	0.000
$0.22\sim0.26$	0.005	0.022	0.001	0.000	0.000	0.000
$0.26\sim0.3$	0.001	0.009	0.001	0.000	0.000	0.000
>0.3	0.001	0.004	0.003	0.000	0.001	0.000

TABLE 4: The value of ζ_{uv} and ζ_{vu} in different working conditions.

r	Conditions					
	ζ_{uv}			ζ_{vu}		
	B25S	B25M	B25L	B25S	B25M	B25L
<-0.1	0.000	0.000	0.000	0.001	0.000	0.001
$-0.1\sim-0.08$	0.003	0.001	0.002	0.006	0.003	0.004
$-0.08\sim-0.06$	0.015	0.010	0.017	0.020	0.014	0.026
$-0.06\sim-0.04$	0.062	0.045	0.074	0.054	0.049	0.089
$-0.04\sim-0.02$	0.145	0.114	0.162	0.118	0.111	0.201
$-0.02\sim0$	0.214	0.188	0.246	0.193	0.180	0.281
$0\sim0.02$	0.222	0.225	0.243	0.230	0.215	0.240
$0.02\sim0.04$	0.168	0.205	0.164	0.191	0.193	0.118
$0.04\sim0.06$	0.103	0.133	0.073	0.113	0.132	0.034
$0.06\sim0.08$	0.048	0.056	0.017	0.050	0.067	0.006
$0.08\sim0.1$	0.016	0.016	0.002	0.018	0.026	0.001
$0.1\sim0.12$	0.004	0.005	0.000	0.005	0.008	0.000
>0.12	0.001	0.001	0.000	0.001	0.002	0.000

C_{uv} and C_{vu} decrease with increasing distance between analytical points, and geometric center points of acquisition window shows that the bigger the distance between two points, the weaker the spatial correlation between pulsating velocity will be. C_{uv} and C_{vu} cloud images are dotted distribution; C_{uv} and C_{vu} near center exist as anisotropy. Along with the increasing average velocity of cross-section, C_{uv} and C_{vu} values first increased and then decreased.

The ζ_{uv} and ζ_{vu} values under different working conditions are shown in Table 4. This proves ζ_{uv} and ζ_{vu} generally

increased first and then decreased with r value increasing. Trends are basically consistent with incremental and decreasing trends, and when $r=0$, ζ_{uv} and ζ_{vu} reach maximum value. Along with the increasing average velocity of cross-section, ζ_{uv} maximum value increases gradually, and ζ_{vu} maximum decreases first and then increases.

3.5. Turbulence Intensity Analysis of Open Channel Flow after Bionic Grass Protection Section. Flow turbulence will cause

FIGURE 9: The distribution of C_{uv} in different working conditions. (a) B25S. (b) B25M. (c) B25L.

FIGURE 10: The distribution of C_{vu} in different working conditions. (a) B25S. (b) B25M. (c) B25L.

additional shear stress and energy consumption, and turbulence intensity is often used to characterize the turbulence characteristics of water flow. Turbulence intensity is the RMS value of the square sum of all fluctuating velocities in this direction during flow fluctuation:

$$u' = \sqrt{\frac{1}{n} \sum_{i=1}^n u_i^2}, \quad (1)$$

$$v' = \sqrt{\frac{1}{n} \sum_{i=1}^n v_i^2},$$

in which u' and v' are the longitudinal and vertical turbulent intensities, respectively, n is the sample capacity, and u and v are the longitudinal and vertical fluctuating velocities, respectively.

3.5.1. Longitudinal Turbulent Intensity. Figure 11 shows the distribution of turbulent intensity along with longitudinal flow after the bionic grass protection section under different working conditions. It can be seen that the turbulence intensity near the bottom of the canal is larger and that near the water surface is smaller; when the incoming flow velocity is small, the longitudinal distribution gradient of the turbulence intensity behind the bionic grass protection section

is larger, and the distribution is oblique. With the increase of the flow velocity, the longitudinal distribution gradient becomes smaller and smaller, and the oblique distribution is not obvious gradually; even when the incoming flow velocity reaches 0.27 m/s, the vertical turbulence intensity appears the maximum.

Figure 12 shows the vertical distribution of longitudinal turbulence intensity after bionic grass protection section under different working conditions ($x = 2$ cm); when velocity is smaller, the distribution of turbulent intensity basically accords with vertical upward, and the longitudinal turbulent intensity curve shows inverted “S” distribution, but when the inflow velocity reaches 0.27 m/s, the turbulence intensity near canal bottom obviously decreases. However, the maximum values appear near the high position of 1/3 grasses. It shows that bionic grass has severe disturbance at this position when the flow velocity is larger.

3.5.2. Vertical Turbulent Intensity. As can be seen from Figure 13, the vertical turbulence intensity near the bottom of the canal near the protective section of bionic grass is larger, and the vertical turbulence intensity increases with the increase of flow velocity. Figure 14 is the vertical distribution of vertical turbulent intensity after the bionic grass protection section under different working conditions ($x = 2$ cm). In Figure 14, there is an obvious difference

FIGURE 11: The distribution of the lateral turbulent intensities in different working conditions. (a) B25S. (b) B25M. (c) B25L.

FIGURE 12: The vertical distribution of the lateral turbulent intensities in different working conditions ($x = 2$ cm).

between vertical turbulent intensities after bionic grass protection section under different flow velocities; with the increase of velocity, the greater the vertical turbulence intensity, the slower the curve and the faster the vertical turbulence intensity changes, and the curve is about exponential distribution; the closer it is to the bottom of the canal, the greater the vertical turbulence intensity.

3.6. Analysis of Reynolds Stress in Open Channel Flow after Bionic Grass Protection Section. In uniform turbulence, the turbulent shear stress τ follows the following formula:

$$\begin{aligned} \frac{\tau}{\rho} &= -\overline{uv} + v \frac{\partial U}{\partial y} \\ &= u_*^2 (1 - \eta). \end{aligned} \quad (2)$$

In the actual process, the velocity gradient is very small, so $v(\partial U / \partial y)$ can ignore it. Formula (2) can be converted into the following form:

$$-\overline{uv} = u_*^2 (1 - \eta). \quad (3)$$

Here, $-\overline{uv}$ is the Reynolds stress, mark as τ_{Re} , and ρ is the density of water.

As can be seen from Figure 15, the Reynolds stress along water depth shows a trend of increasing firstly and then decreases; even some fluids have negative Reynolds stresses, especially when the flow velocity is larger (working condition 3). The momentum exchange in the area of $1 \text{ cm} < y < 3 \text{ cm}$ and some small areas increase the fluid particle velocity. The position of momentum exchange is uncertain and changes with the change of incoming flow velocity, which may be due to the eddy current and the influence of the lodging height of the bionic grass; the position and distribution of the eddy current are different under different incoming flow velocities.

Figure 16 shows the vertical distribution of Reynold's stress after the bionic grass protection section under different working conditions ($x = 2$ cm). As can be seen from Figure 7, the Reynolds stress appears negative at

FIGURE 13: The distribution of the vertical turbulent intensities in different working conditions. (a) B25S. (b) B25M. (c) B25L.

FIGURE 14: The vertical distribution of the vertical turbulent intensities in different working conditions.

1 cm < y < 3.5 cm in operating conditions B25S and B25L. The minus sign indicates that the stress direction is the same as the flow direction, and the momentum exchange in this area is a positive exchange, that is, the velocity tends to increase, but three curves almost coincide with y = 3.5 cm. It shows that the influence of bionic grass on Reynolds stress is highest below 1/2 grass high; at the same time, due to the flexible damping viscosity of bionic grass, the Reynolds stress near the bottom of the canal no longer accords with the distribution law of grass-free flow, and the corresponding Reynolds stress distribution will be locally disturbed under the influence of bionic grass, and the disturbance is more severe when the flow velocity is large.

3.7. Analysis of Turbulent Energy in Open Channel Flow after Bionic Grass Protection Segment. The turbulent kinetic energy is based on the Reynolds time mean point of view, comprehensively considering the pulsation in two directions, and the time mean value is used to express the pulsating force of the flow. Turbulent kinetic energy is called E ,

and it shows the energy of pulsating water masses in a turbulent flow. The expression is

$$E = \frac{(u_i'^2 + v_i'^2)}{2}, \quad (4)$$

in which u_i' and v_i' respectively indicate longitudinal and vertical fluctuating velocity intensities of currents, respectively.

It can be seen from Figure 17 that the maximum turbulent kinetic energy appears near the bottom of the canal or the lodging position of bionic grass, indicating that the momentum exchange of flow particles is intense at these locations.

Figure 18 shows the vertical distribution of turbulent energy of water flow after the bionic grass protection section under different working conditions ($x = 2$ cm). As shown in Figure 9, when the velocity of flow velocity is smaller (working conditions B25S and B25M), the turbulence energy has exponential relation with the depth of water, the turbulence energy increases gradually from top to bottom along

FIGURE 15: The distribution of Reynolds stress in different working conditions. (a) B25S. (b) B25M. (c) B25L.

FIGURE 16: The vertical distribution of Reynolds stress in different working conditions ($x = 2$ cm).

FIGURE 17: The distribution of the kinetic energy in different working conditions. (a) B25S. (b) B25M. (c) B25L.

with water depth, and the maximum turbulence energy appears at channel bottom. When the velocity of the cross-section is larger (working condition is B25L), the relationship between the turbulent energy and the water depth

no longer obeys the exponential relationship. Along the water depth, the turbulent energy increases to a certain peak at first and then decreases and then increases near the bottom of the canal.

FIGURE 18: The vertical distribution of the kinetic energy in different working conditions.

4. Conclusion

In this paper, the longitudinal time-averaged velocity, pulsating velocity probability density, and spatial correlation of flow velocity behind the protective section of bionic grass were analyzed, and the following conclusions were drawn:

- (1) From the measured results of longitudinal velocity distribution, it can be seen that under the influence of bionic grass, the longitudinal velocity distribution has obvious zoning and no longer follows the typical logarithmic distribution law. When the average velocity of the cross-section is small, the longitudinal velocity of the flow near the bottom of the channel is basically linear. Above the 2 cm of the channel bottom, the distribution of the longitudinal velocity is S-shaped. With the increase of the average velocity of the cross-section, the longitudinal velocity near the bottom shows a parabolic distribution along with the water depth, and above the 2 cm of the channel bottom, the vertical distribution of the longitudinal velocity is similar to the S-shaped, and the maximum position of the vertical distribution of the longitudinal velocity is related to the lodging height of the bionic grass.
- (2) The probability density distribution of longitudinal pulsating velocity shows a good symmetry in the histogram, and the distribution curve approximately shows a normal distribution. With the increase of the average velocity of the cross-section, the kurtosis coefficient of the normal distribution decreases, and the trend of the overall peak shape tends to be flatter.
- (3) The innermost circle of C_{uu} and C_{vv} images is roughly rounded, C_{uu} and C_{vv} near the center are isotropic, and the maximum correlation coefficient between C_{uu} and C_{vv} is approximately 0.3. When the

correlation coefficient is approximately 0.02, ζ_{uu} and ζ_{vv} reach maximum value. C_{uv} and C_{vu} cloud images are dotted. C_{uv} and C_{vu} exist anisotropic near center. The maximum correlation coefficient between C_{uv} and C_{vu} is approximately 0.12. ζ_{uv} and ζ_{vu} are greatest when correlation coefficients are about 0.

- (4) When the average velocity of the cross-section is small, the distribution of turbulence intensity increases vertically along the water depth, and the increasing range is approximately parabola. When the velocity of the cross-section is large, the longitudinal turbulence intensity is inverted "S" along the water depth. The vertical distribution curve of the vertical turbulence intensity behind the bionic grass protection section is about exponential distribution. The closer the vertical line is to the lodging position of the bionic grass, the smaller the vertical turbulence intensity is, and the greater the vertical turbulence intensity is near the bottom of the canal. With the increase of the average velocity of the cross-section, the vertical turbulence intensity is greater.
- (5) Flow Reynolds stress after bionic grass protection section shows a variation along water depth firstly and then decreases. When average velocity changes at the cross-section, the currents below 1/2 grasses are mostly affected by water currents.
- (6) When the average velocity of the cross-section is small, there is an exponential relationship between the turbulent kinetic energy and the water depth, and the maximum turbulent kinetic energy is near the bottom of the channel. With the increase of the cross-sectional velocity, the turbulent kinetic energy no longer obeys the exponential relationship.

Data Availability

All data and models used during the study appear in the submitted article. All data and models included in this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the National Natural Science Foundation of China under Grant no. 51709025, the Key Laboratory of Port and Waterway Sediment Engineering Transportation Industry of Nanjing Hydraulic Research Institute, Yk220001-6, the Open Research Fund of Key Laboratory of Failure Mechanism and Safety Control Techniques of Earth-Rock Dam of the Ministry of Water Resources, YK321003, and the basic science and advanced technology research projects of Chongqing Science and Technology Committee, cstc2018jcyjAX0391 and cstc2018jcyjAX0084.

References

- [1] J. Li, Z. Hou, and P. Tian, "Bionic grass protection technology for submarine pipelines under the threat of huge wave erosion," *Coastal Engineering*, vol. 36, no. 4, pp. 37–43, 2017.
- [2] L. Zhuang, J. Yan, F. Fan et al., "Study of artificial seaweeds in hanging segment of submarine pipelines in Maoming single point mooring dock for 30×10^4 t oil unloading," *Ocean Engineering*, vol. 28, no. 2, pp. 76–81, 2010.
- [3] W. Feng, T. Wang, and W. Deng, "A study of the effect of the flexible vegetation on wave absorbing," *Science Technology and Engineering*, vol. 12, no. 26, pp. 6687–6690, 2012.
- [4] Q. Meng and Y. Wu, "Experimental study on wave absorbing characteristics of bionic grass in coastal waters," *Journal of Water Resources and Architectural Engineering*, vol. 12, no. 4, pp. 185–190, 2014.
- [5] J. Lu, H. Xu, and S. Yao, "Turbulent characteristics of flow in river," *Journal of Hydraulic Engineering*, vol. 36, no. 9, pp. 1029–1034, 2005.
- [6] K. Yang, X. Liu, S. Cao, and Z. Zhang, "Turbulence characteristics of overbank flow in compound river channel with vegetated floodplain," *Journal of Hydraulic Engineering*, vol. 36, no. 10, pp. 1263–1268, 2005.
- [7] Y.-H. Li, L. Xie, and T.-c. Su, "Resistance of open-channel flow under the effect of bending deformation of submerged flexible vegetation," *Journal of Hydraulic Research*, vol. 144, no. 3, Article ID 04017072, 2018.
- [8] G. Caroppi, K. Västälä, J. Järvelä, P. M. Rowiński, and M. Giugni, "Turbulence at water-vegetation interface in open channel flow: experiments with natural-like plants," *Advances in Water Resources*, vol. 127, pp. 180–191, 2019.
- [9] V. Chembolu, R. Kakati, and S. Dutta, "A laboratory study of flow characteristics in natural heterogeneous vegetation patches under submerged conditions," *Advances in Water Resources*, vol. 133, Article ID 103418, 2019.
- [10] Y. Zhang, X. Lai, and J. Jiang, "The impact of plant morphology on flow structure: comparative analysis of two types of submerged flexible macrophyte," *Hydrological Sciences Journal*, vol. 61, no. 12, pp. 2226–2236, 2016.