Experimental Study on Flow Resistance Over Rigid Vegetated Channel

XIAO-DONG LIU[1,2], **LIANG-CHUAN TANG**[1], **YU HAN**[1], **JIAN CHEN**[1,3], **AND SHU-QING YANG**[4]

[1]College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
[2]Synergistic Innovation Center of Jiangsu Modern Agricultural Equipment and Technology, Jiangsu University, Zhenjiang 212013, China
[3]State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China
[4]School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW 2522, Australia

Corresponding authors: Yu Han (yhan@cau.edu.cn) and Jian Chen (jchen@cau.edu.cn)

ABSTRACT Vegetation is an important part of the ecological channel, and flow structure over vegetation in ecological channel is rather complex. The vegetation resistance to flow is affected by many factors, and there is still no general calculation method to express it. Thus, it is necessary to explore the mechanism of flow resistance over vegetation in open channel. In this paper, the rigid cylindrical sticks arranged in the open channel were used to simulate the stems of non-submerged vegetation in order to investigate the effects of vegetation on the flow. Through theoretical analysis and experimental verification, it shows the form drag caused by vegetation is closely related to the vortex volume created by vegetation. In addition, the total resistance of vegetated channel can be determined by two methods based on vegetation density and flow resistance partitioning, respectively, and both of them are verified by the experimental results. What's more, for rigid vegetation, the drag coefficient is closely related to vegetation density, spacing between vegetation patches and the Reynolds number. The empirical formula among them was established through the experimental results.

INDEX TERMS Velocity distribution, form drag, resistance partitioning, vortex structure, drag coefficient.

I. INTRODUCTION

Aquatic vegetation is an important part of the ecological channel, and it plays a vital function both on flow environment and ecological restoration. The implantation of vegetation can also bring restoration of biodiversity and the value of ecological services is estimated to be about 10 trillion dollars each year [1]. What's more, the aquatic vegetation in the open channel reduces contaminants and nutrient concentrations in drainage water through physical, chemical and biological mechanisms [2], [3]. However, the threat from vegetation resistance to flow during the flood season has also attracted the attention of conservancy workers. For river systems with flow over vegetation, the flow characteristics are largely controlled by vegetation [4]. Among those characteristics, the flow resistance is the main difference between the smooth and vegetated open channel. Actually, the flow structure over vegetation in an ecological channel is rather complex and it not only dependent on the shape of channel but also on the type of vegetation species and distribution [5]. Thus, it is necessary to explore the mechanical effects of vegetation on the ecological channel flow and try to propose a general expression of flow resistance.

The flow structure is very complicated in vegetated channel as mentioned above. The flow velocity distribution is the most important and direct mean to study the flow structural characteristic, and it is also the basis for studying other flow characteristics. Therefore many scholars have studied the vegetation influence on the flow characteristics in open channel by the flow velocity distribution. Zong *et al.* [6]

conducted laboratory study to describe the flow characteristics and deposition observed in and around a finite patch of vegetation. The velocity distribution in the lateral and longitudinal directions of vegetation patch was measured. The experimental results show flow characteristics of different patch vegetation density and locations of patch vegetation. Huai et al. [7] proposed an analytical model to predict the mean mainstream velocity for double-layered rigid vegetation. The results show there is a significant difference in velocity distribution between the upper and lower vegetation zone due to the existence of vegetation. Meanwhile, Ma [8] also proposed a model based on the non-hydrostatic NHWAVE to predict the velocity distribution, interaction of vegetation and sediments in vegetated open channel. The model can predict the flow velocity distribution in vegetated channel by introducing the vegetation effect on flow resistance into it. The model prediction results are in good agreement with the experimental results. For flow characteristic in vegetated open channels, we observed that the velocity distribution is indeed an important mean to study the influence of vegetation on flow. Therefore, this paper still studies the resistance characteristics of vegetation to flow based on the velocity distribution.

Actually, the total resistance of vegetated open channel contains the skin resistance and form drag. Thus the resistance partitioning theory will provide an important basis for accurate calculation of total resistance. Einstein and Banks [9] is the first to incorporate the contribution of skin friction and form drag to total flow resistance. Since then many researchers have tried to incorporate Einstein's principle into their flow resistance calculations. Nevertheless with the existence of flow regions such as laminar, transitional and fully rough, many of these attempts have failed to incorporate this principle to all the flow regions. Yang and Tan [10] explained how this phenomenon related to the size of flow separation region, and they modified the "summation of resistance components" theory based on the length of flow separation region. This modification enhances the accuracy of Einstein's formula to provide a solid theoretical background to the problem of flow total resistance partitioning. Gamage [11] investigated the skin friction and form drag contributions to total resistance on the roughed channel, which provides an important theoretical guidance for the resistance division of vegetated open channel. Yilmaz [12] conducted a series of experiments to study the effects of skin friction and form drag on open channel flow. The results of this study gave the mathematical expressions of skin resistance and form drag respectively. The results show both forms of resistance are closely related to the Reynolds number and the shape of the vegetation. Vinatier et al. [13] used a terrestrial laser scanner to characterize vegetation-induced flow resistance in a controlled channel. The results show the vegetation pattern, density and flow discharge have important influence on vegetation resistance and offer new possibilities to better link vegetation characteristics and synthetic resistance parameters for hydraulic modeling. ..Mulahasan and Stoesser [14] studied

the flow resistance of in-line vegetation in open channel flow. It indicated the diameter of the rigid emergent vegetation affects a lot on the flow resistance, and the drag coefficient of in-line vegetation exhibits less sensitivity to the vegetation Reynolds number. Based on the above research, the main variables of our experiments mainly include vegetation patch spacing, vegetation density and Reynolds number. From these studies, it indicated although some calculation formulas for vegetation resistance are defined, there are significant differences in the expression of resistance formulas for different experimental conditions and even some conclusions are contradictory. Therefore, a more general method for calculating flow resistance in vegetated channel is needed without involving complicated parameters.

In order to address this question, this paper uses rigid cylindrical sticks to simulate vegetation and aims to explore the potential mechanism of flow resistance over vegetation based on resistance partitioning theory. The total resistance of vegetated channel can be theoretically divided by two parts, i.e., the skin resistance and form drag. The determination of each part can be verified through experiments. In order to verify the rationality of resistance partitioning theory, the total resistance can also be calculated by the vegetation density, which provides a comparison to resistance partitioning results. Finally, based on theoretical analysis and experimental verification for rigid vegetation resistance to flow, we observed the drag coefficient C_D is closely related with vegetation density, spacing of patches and the Reynolds number. The empirical formula among C_D, F_D, and vegetation density λ is established.

II. THEORETICAL METHODS
A. THE TOTAL RESISTANCE DETERMINED BY SKIN RESISTANCE AND FORM DRAG

The Nikuradse's experiments indicate the friction factor is independent of Reynolds number when the Reynolds number is high enough [15]. But Perry et al. [16] analyzed many available experimental data and found this may not be true for flow with ribs or grooves, in which the friction factor is always influenced by the Reynolds number. Actually the resistance of the vegetated open channel includes two parts [17], i.e., skin resistance and form drag. The form drag is closely related the vortex volume near the vegetation [11] and the expression of the skin friction f_{sk} was proposed by Yang et al. [18]. The total resistance with the rib roughness in vegetated open channel can be written as:

$$F = F_{sk} + F_D \tag{1}$$

$$F_D = \rho g V_e i \tag{2}$$

where F = the total resistance of vegetated open channel, F_{sk} = skin resistance, F_D = form drag, $F_{sk} = \tau_{sk} A_{sk}$, τ_{sk} = skin shear force, A_{sk} = liquid/solid contact area, ρ = fluid density, g = gravitational acceleration, V_e = the vortex volume caused by the vegetation, which can be calculated by $V_e = A_e^* k$ (k = the vegetation height in flow), A_e = the area covered by eddies, i = energy slope = the channel slope.

In this paper, all the experiments are conducted in uniform flow. The energy slope equals to the channel slope and the channel slope is measured by the Level instrument.

In addition to form drag, skin resistance is also an important part of total resistance in vegetated open channel, and the skin shear force [15] can be expressed as:

$$\tau_{sk} = \rho u_*^2 \qquad (3)$$

where u_* = friction velocity.

Nikuradse [15] found that the friction factor f_{sk} depends on the velocity and friction velocity, which can be expressed as:

$$u_*^2 = \frac{f_{sk}u^2}{8} \qquad (4)$$

Meanwhile:

$$f_{sk} = \frac{8}{(91.8 - 66.69/R^{+0.72} + 2.5\ln R^+)^2} \qquad (5)$$

where u = the average velocity, $R^+ = u_*h/v$. $u_* = \sqrt{gRi}$, u_* = friction velocity, v = kinematic viscosity coefficient. R = hydraulic radius.

The Eq. (5) can be obtained from Yang *et al.* [18]. It shows R^+ is a pivotal variable for determining the f_{sk}, and the R^+ is also a function of the hydraulic radius R. Therefore, we observed the R plays a crucial role in the calculation of the skin resistance. However, in the vegetated open channel, the hydraulic radius expression based on the cross-sectional area of flow divided by the wet week is no longer applicable. For the uniform flow in open channel, based on the force balance of the channel flow, the Eq. (6) from Han *et al* [19] can be expressed as:

$$\tau_{sk}A = \rho gRiA = \rho gVi \qquad (6)$$

where V = the flow volume in channel.

So the hydraulic radius can be further expressed as:

$$R = V/A \qquad (7)$$

Inserting Eq. (4) and (5) into (3), the improved skin resistance expression can be rewritten as Eq. (8):

$$F_{sk} = \tau_{sk}A_{sk} = \frac{\rho u^2}{A_{sk}(91.8 - 66.69/R^{+0.72} + 2.5\ln R^+)^2} \qquad (8)$$

$$R^+ = u_*h/v = \sqrt{gRi}h/v = \sqrt{gVi/A}h/v \qquad (9)$$

The hydraulic radius R is one of the most important parameters in hydraulics and fluid mechanics. It fully reflects the combined effect of cross-sectional geometry of the flow on overcurrent and flow resistance, which is defined as a ratio of fluid area to a wetted perimeter. However, this definition has no physical implications because it only measures the area and the length. Thus, the hydraulic radius of smooth channel is no longer suitable for the open channel with vegetation. So based on the above analysis, the total resistance of the flow in the vegetated open channel can be obtained by the sum of the skin resistance and the form drag.

B. THE TOTAL RESISTANCE DETERMINED BY VEGETATION DENSITY

Another method for determining the total resistance in vegetated open channel is based on the vegetation density λ. In the steady and uniform open channel flow, the non-submerged cylindrical stems are arranged uniformly over the channel bed. For a control volume of channel flow extending from the channel bed to the flow surface, the momentum balance in the mainstream direction can be written as [20]:

$$\tau = \rho ghi(1 - \lambda h^*) \qquad (10)$$

where τ = the average shear force of the vegetated channel, h = flow depth, h^* = 1 for non-submerged.

Actually, the vegetation resistance and submerged depth of vegetation are closely linked. So the λ should include all the part of liquid/ cylinders contact area, which is redefined as:

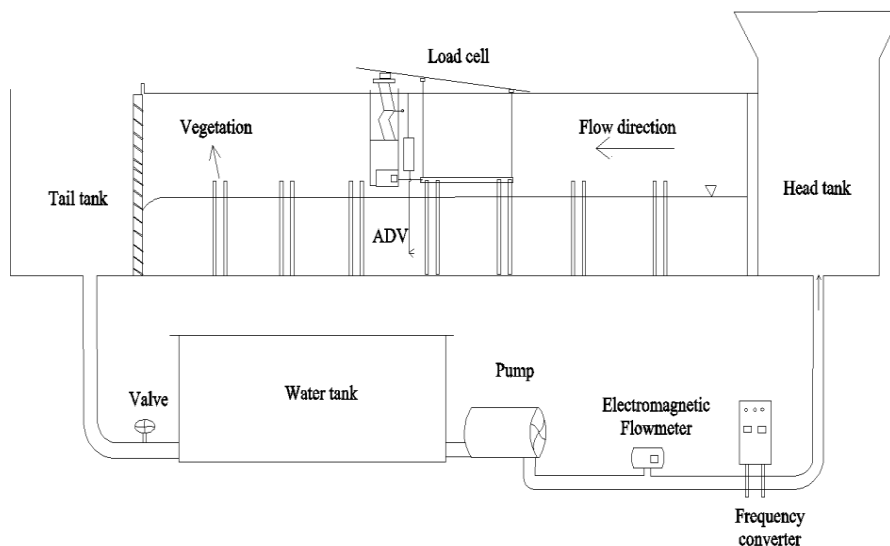$$\lambda = \frac{n}{A_p}\left(\frac{\pi d^2}{4} + \pi dh\right) \qquad (11)$$

where A_p = bed area covered with the array of circular cylinders, n = total number of cylinders in the measuring section, d = stem diameter.

Based on the Eq. (10), the total resistance of vegetated open channels can also be obtained by relative vegetation density λ.

III. EXPERIMENTAL SET UP

Normally the vegetation in an ecological channel exists in patches rather than uniform distribution [21]. Thus, the corresponding experiments to study the resistance characteristics of patch vegetation to flow were conducted. The laboratory experiments were carried out in a 6.3 m long, 0.8 m wide and 0.6 m deep rectangular tilting flume at the Fluid Mechanics Laboratory of the China Agricultural University. The main components of this flume are the head tank, tail tank, glass flow channel and a circular pipe system. The head tank and the tail tank are constructed using stainless steel. The head tank is aligned centrally to the flume and symmetrical to the center line of the channel so that the flow at the entrance of the channel is as uniform as possible. A honeycomb steel plate is located at the entrance of the flume to make the velocity more uniform. A schematic diagram of the entire experimental equipment is shown in Fig.1. The flow depth is controlled by an adjustable tailgate at the end of the flume and the discharge, Q is measured by an electromagnetic flow meter installed in the feeding pipe. The vegetated open channel with load cell is shown in Fig. 2.

A plastic board is installed at the bottom of the channel and the acrylic sticks (d = 0.005 m,) are inserted into the board. In natural river, most vegetation exists in the form of patch. Thus, in this study, the sticks are arranged in an interleaved way. As shown in Fig. 3, one-row vegetation acts as one patch and the spacing between two patches is 0.3 m. The different experimental conditions were conducted by adjusting the discharge Q, the density of vegetation λ, the flow depth h, and the spacing between patches l_2. The Fig.4 shows

the layout of two-row vegetation as one patch. The arrangement of measuring points is shown in Fig.5 and the velocity at the measuring points is measured by Acoustic Doppler Velocity meter (ADV).

Due to the complex flow structure in vegetated open channel, both theoretical formulas and numerical simulations are difficult to give relatively accurate expressions of form drag. So a load cell was designed to measure the form drag caused by vegetation directly. The method of measuring form drag by load cell has been used by previous scholars for several years and it is already a mature and effective method. Kothyari *et al*. [22] and Zhao *et al*. [23] used a similar device to measure vegetation resistance directly, and the good results had been obtained. The accuracy of the load cell used in this paper has been calibrated before the experiment and the device has high sensitivity. The result measured by load cell is the form drag caused by only vegetation patches on load cell rather than all vegetation patches in open channel. The overall structure of the load cell is shown in Fig. 6.

The working principle of the load cell can be described as follows. Firstly, the upper end of the vegetation patches was fixed on an experimental board and the lower end kept a tiny spacing to the channel bed by adjusting the Screw rod as shown in Fig.6. The slider and plastic plate were linked by screw rod. The role of lifting platform is to slightly lift upstream of double axis slide rail to balance the frictional resistance which emerges between the slider and double axis slide rail by the gravity component paralleling to the bottom slope from screw rod and vegetation patch. So the load cell can measured the form drag of vegetation patches on the experimental board. In the experiments, the bottom of the target vegetation patches slightly deviated from the plastic board at the bottom of the channel. The upper end of the vegetation was fixed on the experimental board, and the experimental board was not is not submerged in the flow. The skin friction in this area is from channel bed instead of experimental board so the result of the load cell was only the form drag instead of total drag.

The load cell is connected to and controlled by the computer and the output signal is then captured with an acquisition card at a sampling rate of 25 Hz. All the vegetation

(a)

(b)
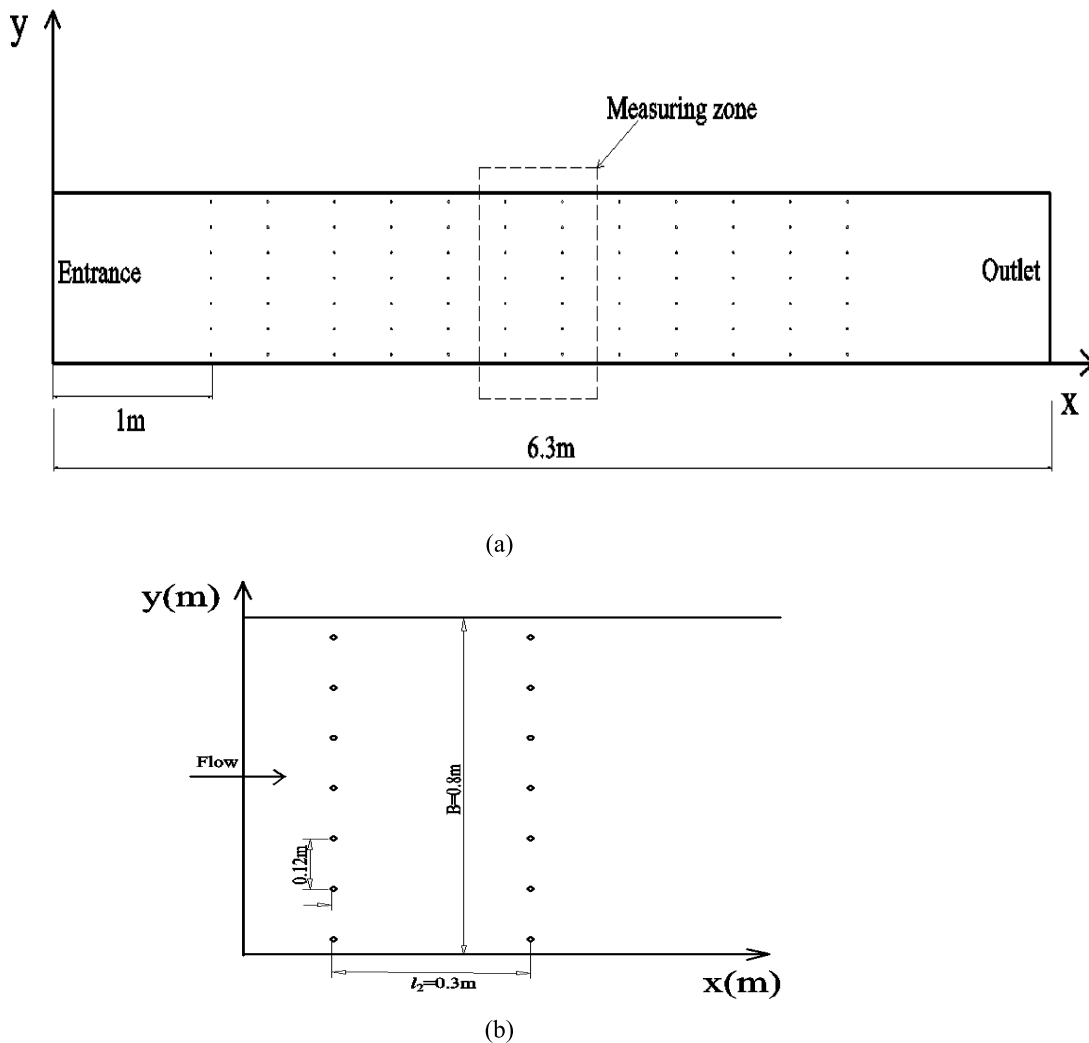
FIGURE 3. The schematic diagram of one-row vegetation as a patch: (a) whole schematic diagram; (b) Measuring zone schematic diagram.

TABLE 1. Four different vegetation arrangements.

| Conditions	l_2 (m)	N row(s) as patch	λ
A(A1~A9)	0.06	1	0.00285
B(B1~B9)	0.18	1	0.000953
C(C1~C9)	0.3	1	0.000359
D(D1~D9)	0.3	2	0.00098

arrangements are shown in the Table 1 and the experimental conditions conducted under each vegetation arrangement are shown in the Table 2.

IV. RESULTS AND DISCUSSION

A. DETERMINATION OF THE LONGITUDINAL SCALE OF THE VORTEX STRUCTURE

An important work of this study is to determine the vortex volume near the vegetation patch by velocity distribution. Although there is currently no determined definition of vortex

structure, it is still very effective to define the size of the vortex structure by the velocity distribution. Many scholars have conducted similar experimental studies on the flow characteristics of patch vegetation based on velocity distribution. The Fig.7 gives the velocity distribution around patch based on Zong *et al.* [6] and Chen *et al.* [24]. The experimental conditions from Meire *et al.* [25] are very similar to this paper, and have detailed measurement results. In order to further rich and verify the theoretical results of this paper, the experimental results of this manuscript are compared with Meire's results. Since there are many experimental conditions involved in this paper, a representative working condition is selected for analysis, and other experimental conditions have similar results. The selected experimental condition is C3 (the $Q = 90 \text{m}^3/\text{h}$, $h = 0.106\text{m}$ and one-row sticks act as one vegetation patch). The spacing between two patches is 0.3m and the vegetation patch located at the $x/d = 0$(x is the distance from the measuring point to vegetation patch). Comparing the results from Meire *et al.* [25] with the experimental results of this paper, the results show that the velocity distribution
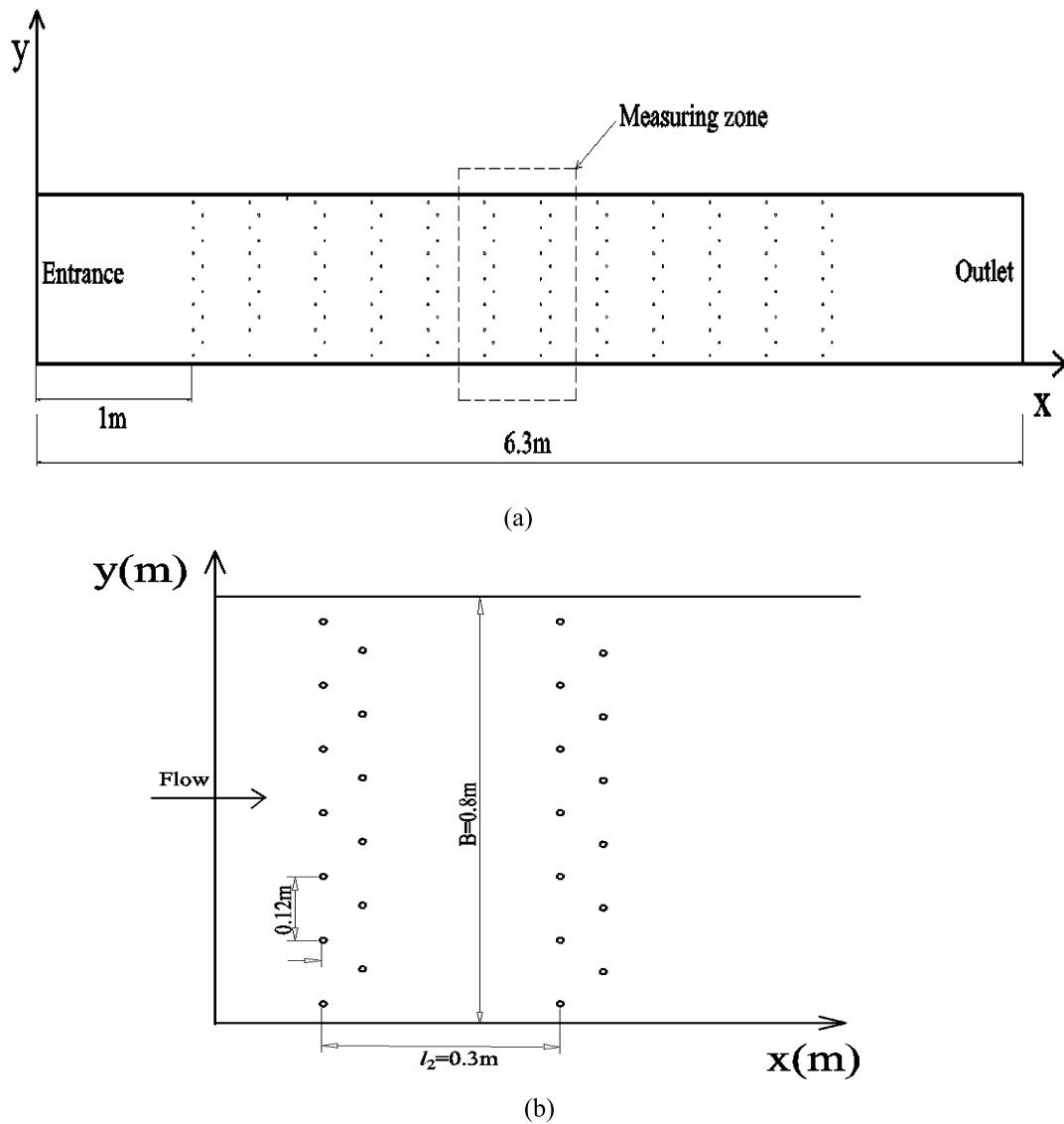
FIGURE 4. The schematic diagram of two-row vegetation as a patch: (a) whole schematic diagram; (b) Measuring zone schematic diagram.

near the patch vegetation achieves a good agreement. The Fig.8 shows the results from Meire's study and this paper under the similar experimental conditions about longitudinal averaging flow velocity distribution at different flow depths. The notation y is the distance of the measuring point from the bottom of the channel.

The Fig.8 shows the length of flow velocity decline of the upstream flow velocity before vegetation patch l_0 and recovery length behind the vegetation patch l_1. By experimental analysis, actually the longitudinal scale of the vortex structure near the vegetation patch is $L'' = l_0 + l_1$. For the experimental condition in the Fig.8, it shows that the longitudinal average velocity begins to decrease gradually at the location $x/d = -7$ and starts to increase at $x/d > 0$ behind the vegetation patch. The velocity begins to stabilize

after $x/d = 22$ and the flow rate recovery rate is reduced to $(\partial(u_x/u_0)/\partial(x/h) < 0.1$ [26]. The u_0 is average velocity in upstream without vegetation and $x =$ the longitudinal distance from the measuring point to upstream patch. Based on the longitudinal scale of the vortex structure L'', the volume of the vortex V_e can be further determined. So the form drag F_D can be calculated by the Eq. (2) further.

In Meire's study, the vegetation patch adopts a circular pattern, and the patches are arranged in the horizontal direction to study the flow velocity distribution under different patch spacing. There are several labels in Fig.8 that need special instructions. The condition1 represents the relative spacing of patch $D/d = 0.5$ and the condition2 represents the relative spacing of patch $D/d = 0$. The notation $D =$ the patch diameter and $d =$ the spacing between two patches.
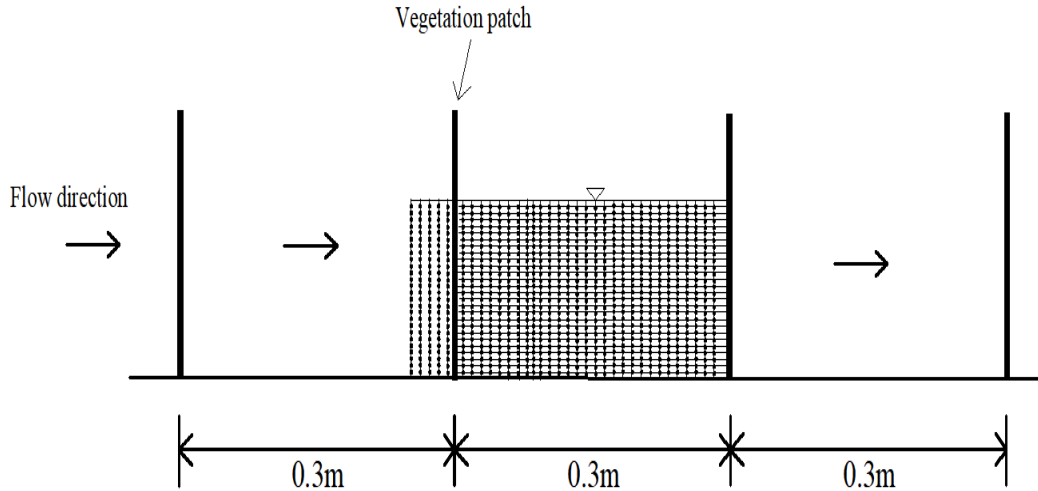
FIGURE 5. The arrangement of measuring points in longitudinal direction.

TABLE 2. Experimental conditions carried out under each vegetation arrangement.

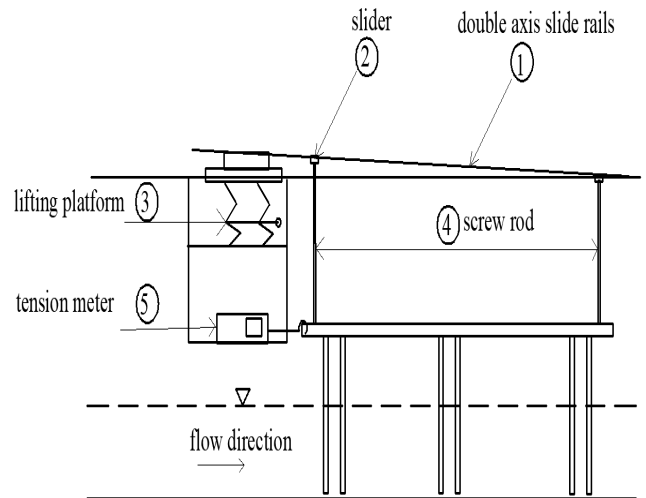| Conditions	Q (m³/h)	h (m)	Re
1	70	0.091	19800
2	80	0.099	22266
3	90	0.106	24703
4	100	0.114	27021
5	110	0.121	29324
6	120	0.128	31565
7	130	0.133	33875
8	140	0.137	36209
9	150	0.143	38367

FIGURE 6. The sketch of the load cell.

The PL and PR represent the left and right sides of a circular vegetation patch respectively. Two group experimental conditions from Meire's study are similar to the experimental conditions in this paper, and all the measured results were carried out by dimensionless treatment. The flow velocity distribution near vegetation patch is shown in the Fig.8. The hollow samples are from Meire's study, and the solid samples are from this paper. From the above comparison, the velocity distribution near vegetation patch follows very similar trend and the experimental results achieve good agreement. However, there is a certain difference at the place where the patch downstream begins. The main reason is that in Meire's experiments, the measuring points are located on both sides of the vegetation patch and the experimental points in this paper are located directly behind the vegetation, so the measurement results will show more reverse flow velocity in this paper. In Meire's study, the vegetation density was larger, which

causes the downstream flow recovery zone behind vegetation patch longer. In general, the flow velocity distribution near the vegetation patch achieves a good agreement.

B. COMPARISON OF CALCULATION OF F_D BY TWO DIFFERENT METHODS

In this paper, two methods based on the vortex volume and load cell have been proposed to obtain the form drag F_D. The calculated results were verified by measured values from load cell. In these experiments, four group experimental conditions are included and each experimental condition includes nine discharges from 70m³/h to 150 m³/h. All the experimental conditions were conducted in uniform flow. The volume of vortex V_e is calculated by analyzing the velocity distribution measured by ADV near the vegetation patch, and thus the form drag F_D can be determined by Eq. (2). Meanwhile, the measured form drag from load cell can be obtained directly.
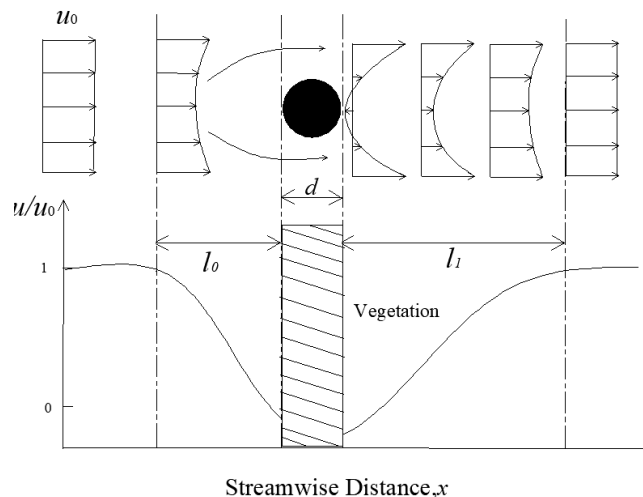
FIGURE 7. The diagram of a typical vortex structure near the vegetation in top view.
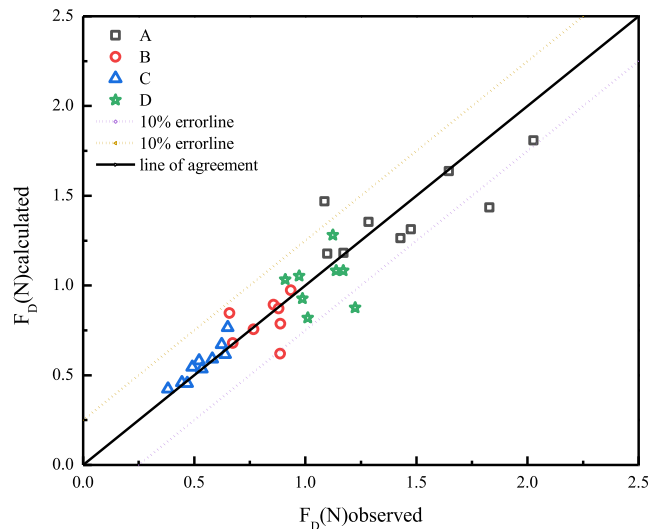

FIGURE 8. Distribution of flow velocity near vegetation.

FIGURE 9. The comparison of measured results with calculated results.

FIGURE 10. The comparison of two different methods of the total resistance.

A comparison of the form drag values from two different methods are shown in Fig. 9.

The Fig. 9 shows the comparison between the obtained theoretical and measured form drag. Most of the experimental points fall within 10% of the error line, which indicates the form drag calculated by the theoretical method show a good agreement with the measured values. Therefore, an accurate measurement of vortex volume near the vegetation patch is of importance for the theoretical results.

C. THE ANALYSIS OF TOTAL RESISTANCE BASED ON THE THEORY OF RESISTANCE PARTITIONING

For the vegetated open channel, the skin resistance can be viewed as the inherent resistance of the channel and the form drag should be viewed as the extra resistance arising from vegetation. The flow resistance of open channel with vegetation includes skin resistance and form drag and the latter accounts for a major part of the total resistance as observed
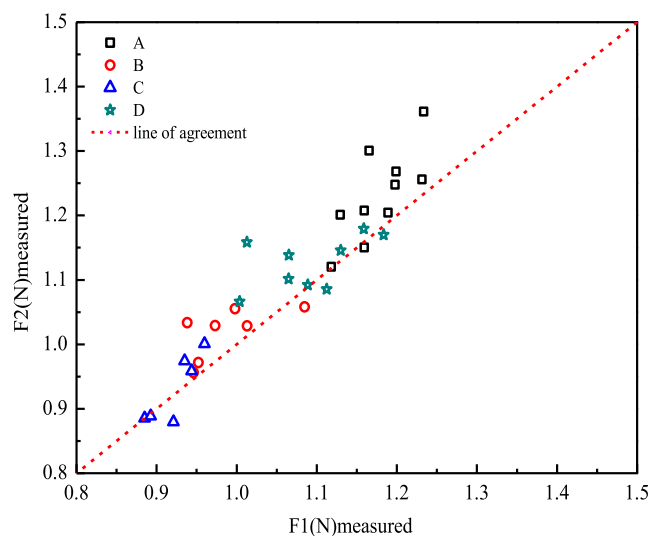
from the previous study [27]. Based on theoretical analysis, the skin resistance can be calculated by Eq. (8). In Eq. (8), the skin resistance is also a function of R^+. So the skin resistance also needs to be determined by the specific size of the vortex structure measured by ADV. So the skin resistance is also the result of the measurement. Furthermore, the measured total resistance can be written as: $F_1 = F_{sk} + F_D$. Meanwhile the total resistance F_2 can also be calculated by Eq. (10).

The Fig. 10 shows the comparison of the two methods of total resistance under different experimental conditions. Here, the experimental conditions were chosen from A, B, C, and D. The results show although there is a certain error between the total resistance results based on two different methods, they all fluctuate near the baseline, which is enough to illustrate the reliability of theoretical analysis. Through analysis, the spacing between two patches corresponding to A is only 0.006 m. As the velocity increases, the flow structure
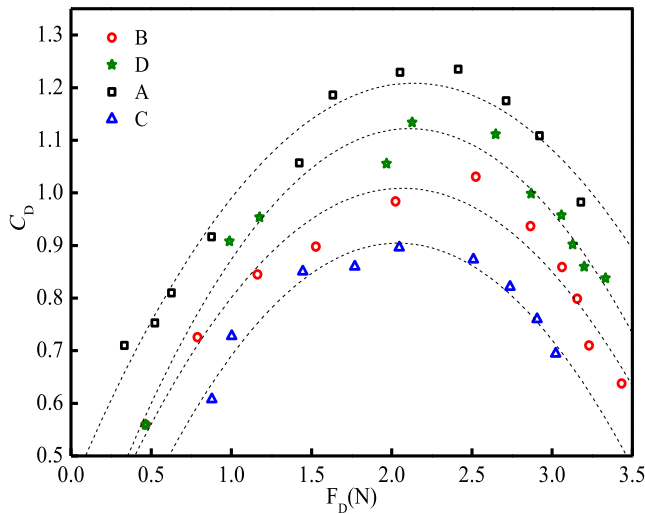
FIGURE 11. The variation of C_D with F_D under different λ for present study.

between the patches wake will affect each other which caused some fluctuation on sticks. It results in a certain extent of error to the load cell. The experimental conditions D also showed a relatively larger fluctuation. We observe although the patch spacing of condition D is relatively large, the two-row vegetation acts as a patch. The flow structure inside the patch changes drastically, causing vibration to the load cell. It causes a certain deviation in the comparison results. Generally, the results of all the experimental conditions achieved a good agreement within a certain range of error, indicating the rationality of resistance partitioning.

D. THE DEPENDENCE OF C_D ON F_D

The form drag coefficient C_D is a very important factor that affects the hydrodynamic characteristics of vegetated flow and it is closely related to the form drag F_D. Cheng and Nguyen [28] considered vegetation hydraulic radius by taking into account the effect of vegetation size, vegetation density, and channel geometry in the computation of drag coefficient, friction coefficient and Reynolds number under emergent condition of flow. Their study reveals that drag coefficient decreases monotonically with Reynolds number. However, the dependence of C_D on F_D was not studied in the past and current experiments. The relationship between the C_D and F_D can be directly represented by the curve lines in the Fig.11. Through the curve lines, it shows that the relationship between the C_D and F_D under different vegetation densities has a very similar trend. Based on the research of the literature Kothyari *et al*. [22], the specific expression of vegetation density λ and drag coefficient C_D have been basically determined. Therefore, the relationship between the C_D and the F_D under different vegetation density λ is further determined by empirical relationship in the paper. Those coefficients are obtained by fitting experimental data. The applicability of these formulas may be limited due to the different experimental conditions, but this paper gives the basic relationship

among the variables, which lays the foundation for further research in the future. The expression of Shear force, τ_D can be written as [29]:

$$\tau_D = \frac{1}{2}\rho C_D n d h u^2 \qquad (12)$$

where τ_D = Shear force caused by vegetation.

Inserting Eq. (2) into (12) yields, the new drag coefficient expression can be expressed as:

$$C_D = (2gV_e i)/(A n d h u^2) \qquad (13)$$

Meanwhile, the corresponding form drag can be measured directly by the load cell and the relation between C_D and F_D is shown in Fig. 11.

The Fig. 11 shows the relation between C_D and F_D under different experimental conditions. We observe there is a clear maximum point at $F = 2N$ and all of them obey approximately the polynomial distribution which can be expressed as:

$$C_D = (1\backslash\lambda) * (-0.18 F_D^2 + 0.18 F_D + 0.34)$$
$$* [0.5\ln(50\lambda) + 0.5] \qquad (14)$$

The basic expression of Eq. (14) refers to Kothyari *et al* [22] research results, and some improvements have been made based this paper study. The Eq. (14) indicates the quantitative relationship on the variation of C_D with F_D and λ. However, the experimental data in the Fig. 11 shows that the drag coefficient C_D gradually increases to a maximum value until $F_D = 2.0N$, and then starts to decrease as F_D continues to increase for a given λ. This because although the rigid sticks are used to simulate the real vegetation and we do not consider the flexible effects of vegetation, the shape of vegetation is more approaching the streamline as the velocity increases. This results in C_D to show a downward trend. At the same time, we can also find that for a given form drag F_D, the drag coefficient C_D increases with the increase of vegetation density λ. The specific vegetation density λ is shown in Table 1.

E. THE VERIFICATION OF THE RELATION BETWEEN THE R^+ AND RELATIVE VORTEX LENGTH L''/l_2

In general, how the R^+ is related with L''/l_2 has not been examined well. By analyzing these two variables, we observe they are all closely related to the size of the vortex structure near the vegetation, and there must be some connection between them. Previous scholars also studied the connection between two variables from Yang *et al* [18]. The theoretical part of this work has been analyzed before by our team. It shows there is a connection between the L''/l_2 and R^+, and the basic form of the formula has been determined. But the specific parameters still do not have a unified standard and the formula has a certain scope of application. Therefore, based on the measured experimental data, the parameters are fitted to provide some resources for the subsequent research. Based on previous research, this paper further analyzes the
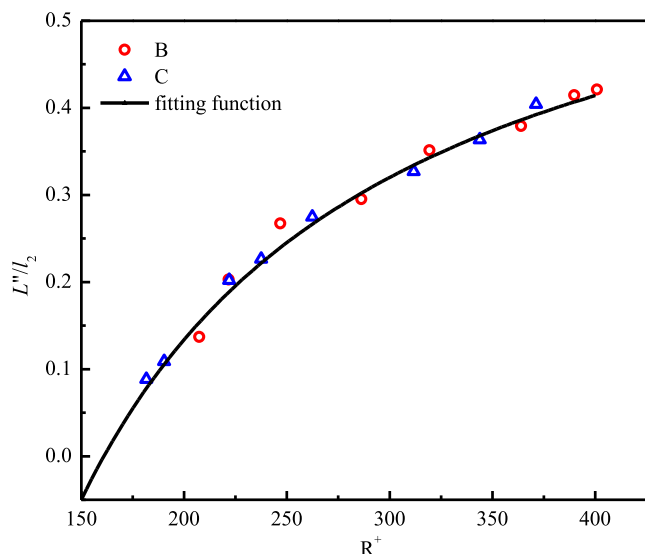
FIGURE 12. The variation of L''/l_2 with R^+.

relationship between R^+ and L''/l_2. The variation of L''/l_2 with R^+ is shown in Fig.12 to illustrate the main observation.

Fig. 12 illustrates the main observation on the variation of L''/l_2 with R^+. L''/l_2 is closely related with the relative density λ, R e and others variables. The relationship between the L''/l_2 with R^+ can be approximately fitted as:

$$L''/l_2 = 16.5*(\frac{R^+}{1+R^+})^{\wedge 7} - 15.8 \qquad (15)$$

By calculation and analysis, the error between the measured and fitted values is only 7%. For the Fig.12, in fact, the relationship between the L''/l_2 and R^+ is only suitable for experimental conditions B and C under the different flow discharges. Because the relationship between L''/l_2 and R^+ is analyzed for the situation that the vortex structure can be fully developed behind vegetation patch. When the vegetation density is too large or the several rows sticks as a vegetation patch, the empirical formula is no longer appropriate again. Therefore, for experimental condition A, the spacing between the patches is small, and the flow structure behind the upstream patch cannot be fully developed under the action of the downstream patch. For working condition D, although the spacing between the two patches is large, due to the two-row vegetation as a patch, the flow structure inside the patch is very complicated and the interaction is obvious. Therefore, Fig.12 only analyzes the two experimental conditions of B and C and the empirical formula was established. Through the analysis of the data in this paper, the application scope of Eq. (15) is further determined.

Actually, the relation between L''/l_2 and R^+ is rather complicated. No explicit formula is currently available to determine the relation for all the experimental conditions. Most of the available formulas from previous research are empirical and based on various functions. However, as the continuous accumulation of experimental data, a relative accurate calculation method will be derived.

V. CONCLUSION

In this paper, a laboratory study was conducted on the flow resistance in a rectangular open channel which was partially filled with artificial non-submerged rigid vegetation patches. The mechanical properties of vegetated channel flow from the aspects of theoretical analysis and experiments were studied in the paper. The main findings of this study are:

(1) The vortex structure near the vegetation patch is determined by the velocity distribution measured by ADV. According to another form of expression hydraulic radius, the calculation formula of the skin resistance has been further corrected. The theoretical equation between the vortex volume and form drag on the flow is established. Also, the results of theoretical analysis are reasonably in good agreement with the experimental values.

(2) The total resistance in the vegetated open channel can be divided into two parts: skin resistance and form drag. The two expressions of total resistance based on vegetation density and the sum of form drag and skin resistance respectively illustrates the rationality of resistance partitioning theory. These two methods are also verified by the experimental data.

(3) The relation between the L''/l_2 and R^+ is further determined and the empirical formula is established. For rigid vegetation, the resistance coefficient, C_D is closely related to the vegetation density, the spacing between vegetation patches and Reynolds number. The relation equation between C_D and those variables was built up.

NOTATION LIST

The following symbols are used in this paper.

A	= liquid/solid contact area (m^2);
A_e	= the area covered by eddies (m^2);
A_p	= bed area covering the array of circular cylinders (m^2);
d	= stem diameter (m);
F	= the total resistance of vegetated open channel (N);
F_{sk}	= skin resistance (N);
F_D	= form drag (N);
F_1	= the measured total resistance by resistance partitioning (N);
F_2	= the calculated total resistance by vegetation density (N);
g	=gravitational acceleration (m/s^2);
$h*$	= the non-submerged degree;
i	=energy slope;
L''	= the longitudinal scale of the vortex structure near the vegetation patch (m);
l_0	= the length of the reduced area of the upstream flow velocity before vegetation patch (m);
l_1	= the length of the recovery area of the flow structure behind vegetation patch (m);

l_2 = the spacing between patches (m);

n = total number of cylinders in this measuring section area;

k = the vegetation height in flow (m);

Q = the discharge (m^3/s);

R = hydraulic radius (m);

x = the longitudinal distance from the measurin point to upstream patch (m);

y = the vertical distance of the measuring point from channel bed (m);

u = the average velocity (m/s);

u_0 = average velocity of upstream without (m/s);

u_* = friction velocity (m/s);

V_e = the vortex volume caused by the vegetation (m^3);

V = fluid volume in vegetated channel (m^3);

v = kinematic viscosity coefficient.

λ = the relative vegetation density;

C_D = drag coefficient;

f_{sk} = friction factor;

τ = the average shear force of the vegetated channel (N/m^2);

τ_D = the shear force caused by vegetation (N/m^2);

τ_{sk} = skin shear force (N/m^2);

ρ = fluid density (kg/m^3);

REFERENCES

[1] R. Costanza, R. D'Arge c, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt, "The value of the world's ecosystem services and natural capital," *Ecological Econ.*, vol. 25, no. 1, pp. 3–15, 1997.

[2] J. S. Thullen, J. J. Sartoris, and S. M. Nelson, "Managing vegetation in surface-flow wastewater-treatment wetlands for optimal treatment performance," *Ecological Eng.*, vol. 25, no. 5, pp. 583–593, 2005.

[3] R. H. Kadlec and R. L. Knight, "Treatment wetlands," *Soil Sci.*, vol. 162, no. 6, pp. 233–248, 1995.

[4] J. Horppila and L. Nurminen, "Effects of submerged macrophytes on sediment resuspension and internal phosphorus loading in Lake Hiidenvesi (southern Finland)," *Water Res.*, vol. 37, no. 18, pp. 4468–4474, 2003.

[5] W.-U. Long-Hua and X.-L. Yang, "Factors influencing bending rigidity of submerged vegetation," *J. Hydrodynamics, Ser. B*, vol. 23, no. 6, pp. 723–729, 2011.

[6] L. Zong and H. Nepf, "Flow and deposition in and around a finite patch of vegetation," *Geomorphology*, vol. 116, nos. 3–4, pp. 363–372, 2010.

[7] W. Huai, W. Wang, Y. Hu, Y. Zeng, and Z. Yang, "Analytical model of the mean velocity distribution in an open channel with double-layered rigid vegetation," *Adv. Water Resour.*, vol. 69, no. 4, pp. 106–113, 2014.

[8] G. Ma, "Modeling wave damping and sediment transport within a patch of vegetation," *Coastal Eng. Proc.*, vol. 1, no. 34, p. 17, 2014.

[9] H. A. Einstein and R. B. Banks, "Fluid resistance of composite roughness," *Trans. Amer. Geophys. Union*, vol. 31, no. 4, pp. 603–610, 1950.

[10] S.-Q. Yang and S.-K. Tan, "Flow resistance over mobile bed in an openchannel flow," *Water Resour. Res.*, vol. 134, no. 7, pp. 937–947, 2008.

[11] N. C. D. K. L. Gamage, *Macro Turbulent Characteristics Over Two-Dimensional Bed Forms and Its Skin Friction and Form Drag Separation*, 2012.

[12] N. A. Yilmaz, "Fluid mud gravity currents through emergent aquatic vegetation," Ph.D. dissertation, Gradworks, 2014.

[13] F. Vinatier, J.-S. Bailly, G. Belaud, and D. Combemale, "Using a terrestrial laser scanner to characterize vegetation-induced flow resistance in a controlled channel," Jul. 2016, *arXiv:1608.02483*. [Online]. Available: https://arxiv.org/abs/1608.02483

[14] S. Mulahasan and T. Stoesser, "Flow resistance of in-line vegetation in open channel flow," *Int. J. River Basin Manage.*, vol. 15, no. 3, pp. 329–334, 2017.

[15] J. Nikuradse, "Laws of flow in rough pipes," Tech. Rep. Arch. Image Library, Washington, DC, USA, Tech. Rep. 3, 1950.

[16] A. E. Perry, W. H. Schofield, and P. N. Joubert, "Rough wall turbulent boundary layers," *J. Fluid Mech.*, vol. 37, no. 2, pp. 383–413, 2006.

[17] S.-Q. Yang, S.-K. Tan, S.-Y. Lim, and S.-F. Zhang, "Velocity distribution in combined wave–current flows," *Adv. Water Resour.*, vol. 29, no. 8, pp. 1196–1208, 2006.

[18] S.-Q. Yang, Y. Han, and N. Dharmasiri, "Flow resistance over fixed roughness elements," *J. Hydraulic Res.*, vol. 49, no. 2, pp. 257–262, 2011.

[19] Y. Han, S. Q. Yang, L. C. Qiu, and N. Dharmasiri, "Flow resistance over submerged vegetation in ecological channel," in *Proc. IOP Conf. Ser., Earth Environ. Sci.*, 2017, pp. 1–11.

[20] B. M. Stone and H. T. Shen, "Hydraulic resistance of flow in channels with cylindrical roughness," *Journal Hydraulic Eng.* vol. 128, no. 5, pp. 500–506, 2002.

[21] T. J. Bouma, L. A. Van Duren, S. Temmerman, T. Claverie, A. Blanco-Garcia, T. Ysebaert, and P. M. J. Herman, "Spatial flow and sedimentation patterns within patches of epibenthic structures: Combining field, flume and modelling experiments," *Continental Shelf Res.*, vol. 27, no. 8, pp. 1020–1045, 2007.

[22] U. C. Kothyari, K. Hayashi, and H. Hashimoto, "Drag coefficient of unsubmerged rigid vegetation stems in open channel flows," *J. Hydraulic Res.*, vol. 48, no. 6, pp. 691–699, 2010.

[23] K. Zhao, N.-S. Cheng, X. Wang, and S. K. Tan, "Measurements of fluctuation in drag acting on rigid cylinder array in open channel flow," *J. Hydraulic Eng.*, vol. 140, no. 1, pp. 48–55, 2014.

[24] Z. Chen, A. Ortiz, L. Zong, and H. Nepf, "The wake structure behind a porous obstruction and its implications for deposition near a finite patch of emergent vegetation," *Water Resour. Res.*, vol. 48, no. 9, p. 9517, 2012.

[25] D. W. S. A. Meire, J. M. Kondziolka, and H. M. Nepf, "Interaction between neighboring vegetation patches: Impact on flow and deposition," *Water Resour. Res.*, vol. 50, no. 5, pp. 3809–3825, 2014.

[26] Y. Tanino and H. M. Nepf, "Laboratory investigation of mean drag in a random array of rigid, emergent cylinders," *J. Hydraulic Eng.*, vol. 134, no. 1, pp. 34–41, 2008.

[27] M. Righetti, "Flow analysis in a channel with flexible vegetation using double-averaging method," *Acta Geophys.*, vol. 56, no. 3, pp. 801–823, 2008.

[28] N.-S. Cheng and H. T. Nguyen "Hydraulic radius for evaluating resistance induced by simulated emergent vegetation in open-channel flows," *J. Hydraulic Eng.*, vol. 137, no. 137, pp. 995–1004, 2011.

[29] R. J. Garde, "Mechanics of Sediment Transportation and Alluvial Stream Problems," *Eng. Geol.*, vol. 14, no. 4, pp. 283–284, 1977.
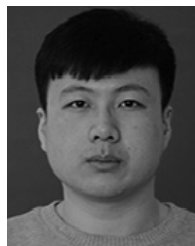
XIAO-DONG LIU was born in He Bei province, China, in 1993. He is currently pursuing the Ph.D. degree from China Agricultural University and has been engaged in the design and research of ecological channels. He has a solid theoretical foundation in the field, published relevant articles, and applied for related patents. The research and design work of this experiment were completed with the help of him and the instructor, and his research work has been recognized by relevant scholars. Research on flexible vegetation in open channels is currently underway and some results have been achieved.

LIANG-CHUAN TANG was born in Chengdu, Sichuan, China, in 1995. He is currently pursuing the master's degree in water conservancy and hydropower engineering with the College of Water Resources & Civil Engineering, China Agricultural University, Beijing, China. His current research interests include resistance of vegetated channel and investigation of open channel turbulence structures in terms of the presence of complex bed forms.

YU HAN received the Ph.D. degree in hydraulic engineering from Wollongong University, New South Wales, Australia. She is currently an Associate Professor with the College of Water Resources & Civil Engineering, China Agricultural University, Beijing, China. She has authored 1 book chapter, over 30 papers, and holds 3 patents. Her current research interests include investigation of open channel turbulence structures in terms of the presence of complex bed forms and development of a novel mathematical model to predict on the boundary shear stress in terms of momentum balance mechanism.

SHU-QING YANG is the Professor with the School of Civil, Mining & Environmental Engineering, University of Wollongong, New South Wales, Australia. He has made tremendous contributions to the research and design of the ecological environment, and is a famous leader in this field. He has authored 5 book chapters, over 80 papers. At the same time, many articles have been published in the journals of high impact factors. He has very important guiding suggestions for this article. Under the guidance of his solid theoretical foundation, this research work has achieved a very important breakthrough.

● ● ●

JIAN CHEN received the Ph.D. degree in guidance, navigation, and control from Beihang University (BUAA), Beijing, China. He is currently an Associate Professor and the Ph.D. Advisor with the Intelligent Control and Unmanned Systems Research Center, College of Engineering, China Agricultural University, Beijing, China. He has authored 4 book chapters, over 70 papers, and holds 3 patents. His current research interests include guidance, navigation and control of unmanned systems, intelligent control and optimization, deep learning based remote sensing, simultaneous localization and mapping of unmanned systems, application technology of precision agricultural aviation, and integrated space-air-ground-water cooperative sensing and multi-agent system cooperative control.