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The streamwise velocity distribution in a two-stage channel with ice cover

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ABSTRACT

The problem of agricultural non-point source pollution has become increasingly serious. How to determine the ecological drainage ditch system is one of the effective methods to solve the agricultural non-point source pollution. This research study focuses on the velocity distribution in a two-stage section ecological channel with ice cover. The results show that the two-stage section channel with ice cover can effectively reduce the flow velocity in the channel and increase the retention time of water in the channel. By comparing with the experimental data, the accuracy of the analytical solution is high, which provides a theoretical reference for the transport of sediment and pollutions in a two-stage section channel with ice cover in the future.

Key words: analytical solution, ice cover, non-point source pollution, streamwise velocity, two-stage channel

HIGHLIGHTS

- Discuss the transverse velocity distribution law in a two-stage channel with ice cover.
- Give the analytical solution of the transverse velocity distribution.

1. INTRODUCTION

With the increasingly serious agricultural soil erosion and non-point source pollution, more and more technologies have been applied to agricultural drainage (Dolan & Mcgunagle 2005; Vidon *et al.* 2012). In recent years, ecological channels have been widely used in practical projects because of their ecological friendliness, and can better solve the problems of agricultural non-point source pollution (Kumwimba *et al.* 2017). In recent years, the research of two-stage section ecological channel has been widely concerned (Chen 2013; Zeng *et al.* 2014; Huang *et al.* 2020).

A two-stage section drainage ditch is a better option than a traditional trapezoidal ditch, because it meets drainage requirements while eliminating sediment and nutrient losses (Västilä & Järvelä 2011; Christopher *et al.* 2017; Kumwimba *et al.* 2018). For example, Hodaj *et al.* (2017) proved that the two-stage ditch can significantly reduce the concentrations of total suspended sediment, nitrate nitrogen, soluble reactive phosphorus and total phosphorus in the drainage. Roley *et al.* (2016) and Krider *et al.* (2017) also proposed similar results. At the same time, vegetation on the floodplain has a positive impact on water quality by reducing pollution, improving river bed stability, assisting drainage restoration and controlling flow velocity (Folkard 2011; Davis *et al.* 2015; Mahl *et al.* 2015). For a two-stage section channel, the streamwise velocity distribution is more complicated. Due to the different water depth across the channel, it can produce a mixed layer near the interface between the main channel and the floodplain, and secondary flow occurs (Stephenson & Kolovopoulos 1990).

In higher latitude areas, rivers usually freeze in winter, because the river surface icing will lead to great changes in the hydraulic characteristics of the channel, just like adding artificial floating islands on the river surface (Li *et al.* 2010; Zhou & Wang 2010). It is generally believed that after adding the ice cover, the flow in the channel can be approximately regarded as two layers (Zhu *et al.* 2011; Zhao *et al.* 2012; Xavier *et al.* 2018; Liu *et al.* 2019), and then the vertical velocity can be calculated (Lau 1982; Urroz & Ettema 1994). However, it is more difficult to calculate the velocity in the channel with two-stage section after adding ice cover, because the lower boundary conditions are more complex. In this paper, the five experiment discharge conditions of a channel with ice cover and two-stage section are conducted, and the transverse velocity is measured. The aims of this paper are: (1) to explore transverse distribution of velocity in the two-stage channel with ice cover; (2) to obtain the analytic solution of the transverse velocity of the two-stage section channel with the ice cover.

2. STUDY METHODS

2.1. Experiments set

The experiment was carried out in the laboratory of Zhejiang University of Water Resources and Hydropower. The width of the laboratory flume is 40 cm, foam board represents ice cover, and plexiglass is used for the two-stage section (Figure 1). The method of combining ice cover with the two-stage cross-section channel was used in the experiment. The slope S_0 is 0.0005 and the water depth can be adjusted by the tail gate at the end of the flume. The measuring section with x = 5.1 m is measured by LS1206B current meter, and the measurement error is 1.5% by manufacturer. Five tests have been carried out in this study. The flow parameters are shown in Table 1. In previous works (Wood & Liang 1989; Lin & Shiono 1995; Simoes & Wang 1997; Guan 2003; Farzadkhoo *et al.* 2018; Gu *et al.* 2018; Bai & Zeng 2019), the width of floodplain varied from 0.1 m to 2.5 m. Here, the width of the floodplain is 0.1 m, and its height is 10 cm. The width of the main channel is 30 cm.

2.2. Analytical solution

For steady uniform flow in a compound channel, the resultant surface force on an elementary volume must be equal to the body force in the main flow direction. The simple two-stage flow function can be described by the Shiono and Knight Model (SKM) (Rameshwaran & Shiono 2007). One considers the water body with the length of *dx*, the width of *dy*, and the height of *H(y)* (Yang *et al.* 2013). The following Equation (1) is a balance equation between shear stresses, and the product ρgHS_0 is the shear stress exerted by the flow in the flow direction:

$$\rho gHS_0 + \frac{\partial H\overline{\tau_{xy}}}{\partial y} - \tau_{bz} = \frac{\partial(\rho HKU_d^2)}{\partial y} \tag{1}$$

where ρ is the density of water; g is the gravitational acceleration; S_0 is the longitudinal bed slope; $\partial(\rho HKU^2)/\partial y$ is the secondary current term; τ_{bz} is the boundary shear stress of the channel bed in the plane perpendicular to z-direction; $\overline{\tau_{xy}}$ denotes the shear stress in the x-direction in the plane perpendicular to the y direction, K is secondary current coefficient, which expresses the influence of the secondary flow between the floodplain and the main trough on the lateral distribution of velocity; U_d is the depth-averaged velocity in the main flow direction.

After adding ice cover, shear force τ_{za} of ice cover should be added:

$$\rho gHS_0 + \frac{\partial H\overline{\tau_{xy}}}{\partial y} - \tau_{bz} - \tau_{az} = \frac{\partial(\rho HKU_d^2)}{\partial y} \tag{2}$$

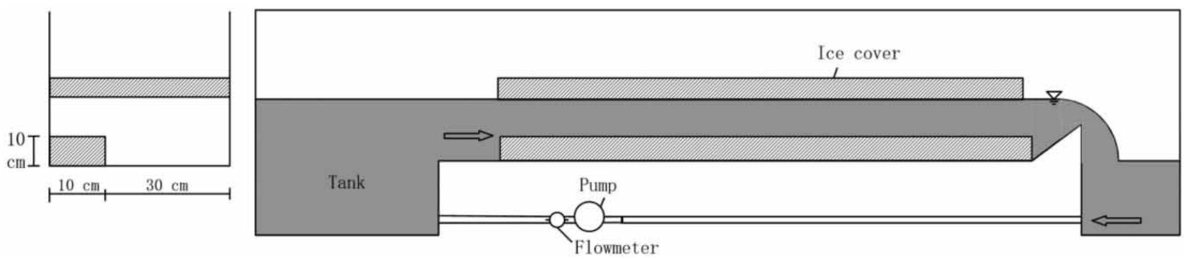

Figure 1 | The structure of the experimental channel.

Table 1 | Experimental parameters of flow

Run	Channel	Discharge (L/s)	Water depth (cm)	B (cm)	S_0
1	Two-stage	7.3	15.4	40	0.0005
2	Two-stage	9.1	16.7	40	0.0005
3	Two-stage	11.2	18.2	40	0.0005
4	Two-stage	13.1	19.4	40	0.0005
5	Two-stage	14.9	20.7	40	0.0005

where $\overline{\tau_{xy}} = \rho\zeta_{yx}\partial U/\partial y$; $\zeta_{yx} = \xi H U_*$; U_* is the shear velocity; ξ is the eddy viscosity coefficient; H is the water depth (Nie *et al.* 2017).

The U_{*a}, and U_{*b} are shear velocity of ice cover and channel bed that can be obtained by solving the following equations (Parthasarathy & Muste 1994):

$$U_* = \sqrt{U_{*a}^2 + U_{*b}^2} \tag{3}$$

U_{*i} $(i = a,\ \ b)$ can be defined as (Rijn 1984)

$$U_{*i} = \left(\frac{f_i}{8}\right)^{1/2} U_d \tag{4}$$

Then

$$U_* = \sqrt{\frac{f_a + f_b}{8}} U_d \tag{5}$$

$$\zeta_{yx} = \xi H \sqrt{\frac{f_a + f_b}{8}} U_d \tag{6}$$

For shear stress τ_{iz} $(i = a,\ b)$

$$\tau_{iz} = \frac{1}{8}\rho f_i U_d^2 \tag{7}$$

where f_i is the Darcy-Weisbach friction factor of channel bed and ice cover.

Equation (2) can be solved as

$$\rho g H S_0 + \frac{\partial}{\partial y}\left(\xi H^2 \left(\frac{f_a + f_b}{8}\right)^{1/2} U_d \frac{\partial U_d}{\partial y} - \rho H K U_d^2\right) - \frac{1}{8}\rho (f_a + f_b) U_d^2 = 0 \tag{8}$$

where U_d is the depth-averaged velocity.

We define $f = f_a + f_b$, then it can be changed as

$$\rho g H S_0 + \frac{\partial}{\partial y}\left(\xi H^2 \left(\frac{f}{8}\right)^{1/2} U_d \frac{\partial U_d}{\partial y} - \rho H K U_d^2\right) - \frac{1}{8}\rho f U_d^2 = 0 \tag{9}$$

To solve Equation (9), we can get

$$U_d = (\vartheta_1 + C_1 e^{\beta y} + C_2 e^{\gamma y})^{1/2} \tag{10}$$

where $\beta = \tau_2 + \sqrt{\tau_2^2 + \tau_1 1/2\rho f}/2\tau_1$, $\gamma = \tau_2 - \sqrt{\tau_2^2 + \tau_1 1/2\rho f}/2\tau_1$, $\tau_1 = 1/2\rho\xi H^2 (f/8)^{1/2}$, $\tau_2 = \rho H K$, $\vartheta_1 = 8gHS_0/f$, C_1, C_2 are integral constants determined by boundary conditions.

2.3. Boundary conditions

The analytic solutions can be obtained by dividing the compound channel into two subareas (one is the main channel and the other is the floodplain). Boundary conditions are as follows:

(i) For a symmetric channel, the lateral gradient of velocity at the centerline of the main channel is zero.

(ii) The joint of the two domains must satisfy the velocity continuity, i.e., $(U_d)^i = (U_d)^{i+1}$, $(\partial U_d/\partial y)^i = (\partial U_d/\partial y)^{i+1}$.
(iii) The depth-averaged streamwise velocity must be zero at the far side of the floodplain, i.e., $U_d = 0$.

2.4. Parameter determination and model application

2.4.1. Friction factor

The friction coefficient f_i can be described by Rameshwaran & Shiono (2007)

$$f_i = \left(-2\ \log\left(\frac{3.02\nu}{\sqrt{128gH^3S_0}} + \frac{k_s}{12.3H}\right)\right)^{-2} \tag{11}$$

where k_{si} $(i = a, b)$ is the equivalent roughness height for ice cover and channel bed, and ν is flow kinematic viscosity.

$$k_{si} = (8.25n_i\sqrt{g})^6 \tag{12}$$

where n_i $(i = a, b)$ is Manning's number for ice cover and channel bed.

2.4.2. Eddy viscosity coefficient

The lateral eddy viscosity coefficient in a compound channel can be calculated as (Abril & Knight 2004) follows:

$$\xi = \kappa/6, \tag{13}$$

where $k = 0.4$ is the von Karman constant.

2.4.3. Secondary current coefficient

The secondary current coefficient K was empirically calibrated in order to give the best fit with the experimental data.

2.5. Error analysis

Error analysis was conducted to determine the difference between the predicted and measured data of depth-averaged velocity. The root mean square error $RMSE$ and coefficient of determination R^2 were calculated by the following equations:

$$R^2 = 1 - \frac{SSE}{SST} \tag{14}$$

$$SST = \sum_{i=1}^{N} (Y_i - meanY)^2 \tag{15}$$

$$SSE = \sum_{i=1}^{N} (Y_i - X_i)^2 \tag{16}$$

$$meanY = \frac{1}{N}\sum_{i=1}^{N} Y_i \tag{17}$$

$$RMSE = \sqrt{\frac{\sum_{1}^{N} (X - Y)^2}{N}} \tag{18}$$

where N is the number of lateral measuring points; X is the calculated value and Y is the measured value of depth-averaged velocity.

3. RESULTS AND DISCUSSION

The experimental and predicted lateral distributions of streamwise velocity in a two-stage section channel with ice cover were compared, and results are shown in Figures 2–6. In general, the predicted data agrees well with the experimental data, and the velocity in the main channel is much larger than that in the floodplain area. The error statistics of the analytic model are

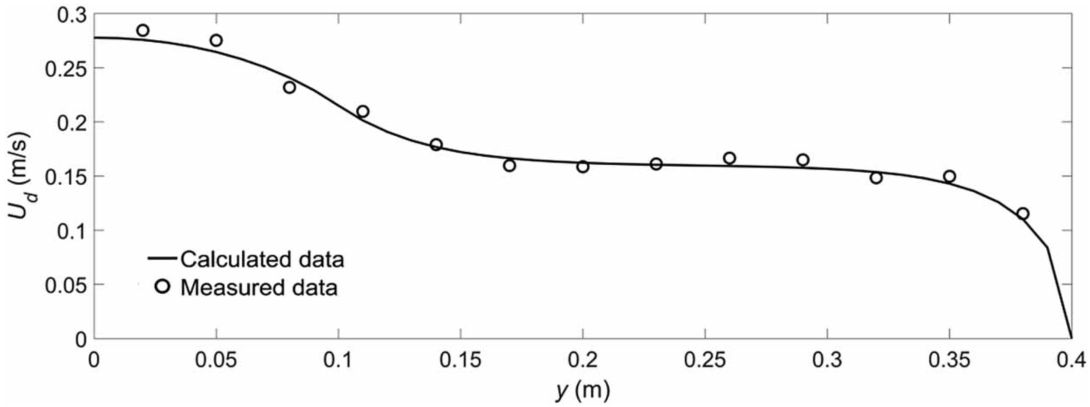

Figure 2 | Comparison between calculated and measured velocity U_d (m/s) of Run 1.

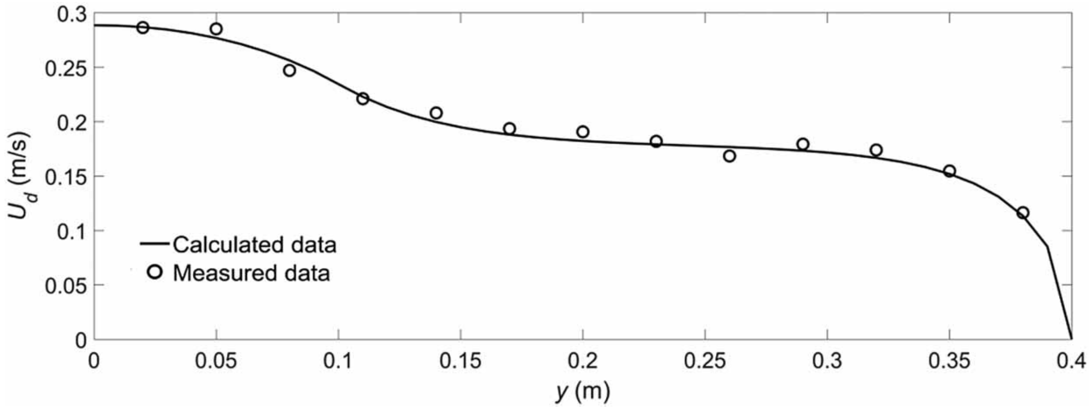

Figure 3 | Comparison between calculated and measured velocity U_d (m/s) of Run 2.

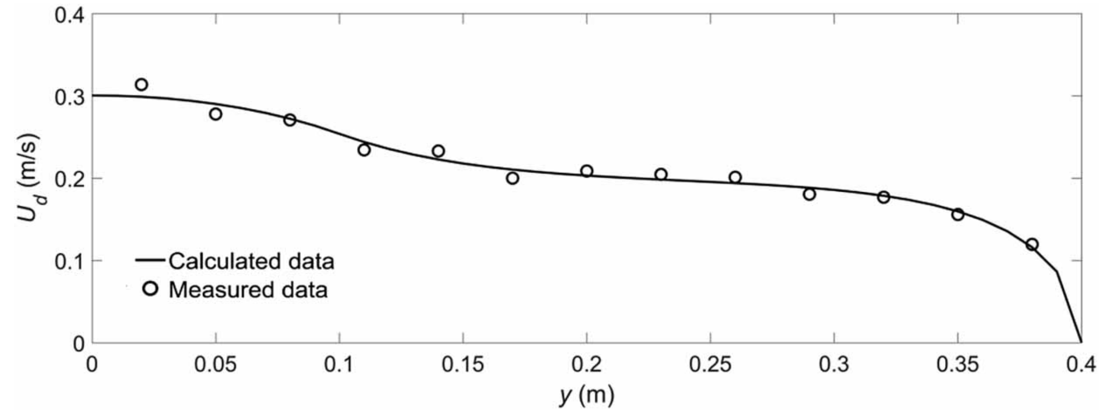

Figure 4 | Comparison between calculated and measured velocity U_d (m/s) of Run 3.

shown in Table 2. Each model has a good prediction compared with the measured data, and *RMSE* of the model range from 0.0062 to 0.0083. Coefficients of determination R^2 of the model are over 0.9727.

The results show that the transverse distribution of velocity in the compound channel with ice cover is similar to that in the conventional compound channel, and the main channel is obviously larger than the floodplain (Chen 2013; Zeng *et al.* 2014;

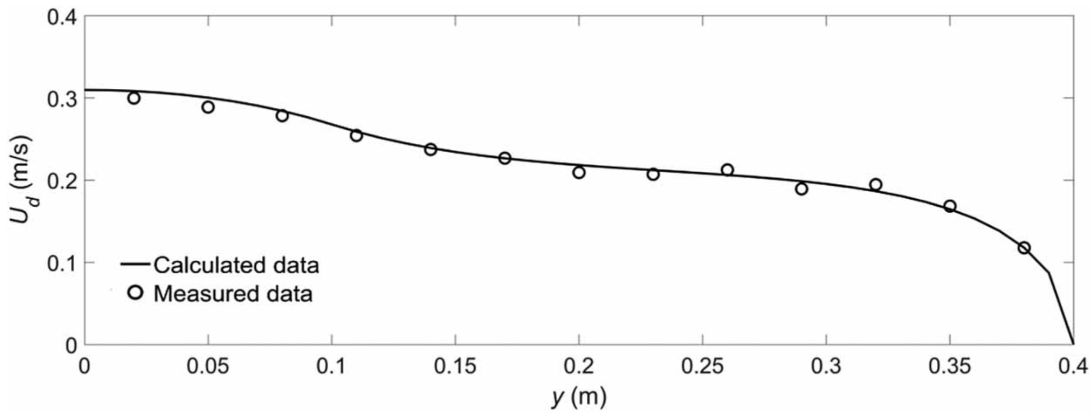

Figure 5 | Comparison between calculated and measured velocity U_d (m/s) of Run 4.

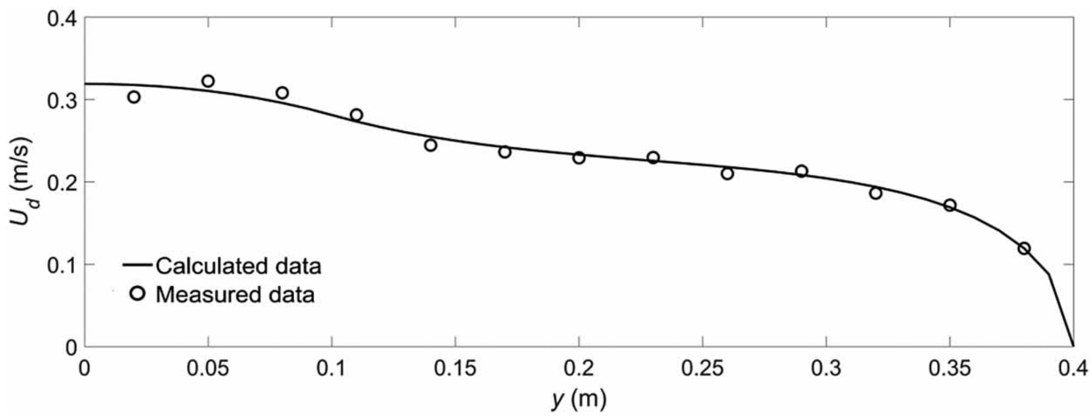

Figure 6 | Comparison between calculated and measured velocity U_d (m/s) of Run 5.

Table 2 | Error statistical analysis and secondary current coefficient

Run	1	2	3	4	5
RMSE	0.0068	0.0062	0.0083	0.0067	0.0083
R^2	0.9791	0.9832	0.9727	0.9837	0.977
K_{mc} (%)	2.34	2.57	2.95	3.03	3.23

Huang *et al.* 2020). At the same time, the solution of the transverse velocity distribution is similar to the solution of the transverse velocity distribution of the common compound channel. According to the force balance analysis of the fluid divided into elementary volumes, the solution is divided into sections (Rameshwaran & Shiono 2007). In this paper, the influence of the ice sheet is added to the conventional Equation (2). For the channel with ice cover, the ice cover can significantly increase the water depth and reduce the average velocity of the channel (Bai *et al.* 2020), and the composite section with ice cover also conforms to this rule. In this paper, the characteristic of the ice cover and the compound channel on the velocity has been taken into account when solving the transverse velocity distribution in the compound channel with ice cover, and a high simulation accuracy is obtained (Table 2).

In the two-stage section channel with ice cover, the water depth is obviously larger than that of the simple two-stage section channel. This is because the ice cover is equivalent to adding a boundary, which increases the channel roughness (Xavier *et al.* 2018; Liu *et al.* 2019), and it will increase the retention time of water flow, and is more conducive to retaining sediment and nutrients. For the secondary current coefficient, secondary current coefficient in the floodplain $K_{fp} = 0$ is assumed considering the small velocity in that region. For the main channel, a difference from the suggested value could be obtained by Ervine *et al.* (2000), i.e., secondary current coefficient in main channel $K_{mc} < 0.5\%$ for straight compound channels. The secondary current coefficient of the two-stage section channel with ice cover is more than 2.34%, which proves that the influence factors of the secondary current in the two-stage section channel with ice cover are relatively bigger. The transverse velocity distribution in two-stage section channels with ice cover will be more uniform.

This study aims mainly at the change of hydraulic characteristics of non-vegetated compound section channels after freezing. In some compound channels, vegetation often grows on the floodplains. Vegetation will block the flow on the floodplain, and further reduce the flow velocity on the floodplain (Huai *et al.* 2008, 2009). Flexible or rigid vegetation (Chapman *et al.* 2015), different arrangements (Zhang *et al.* 2018), submerged or non-submerged state (Liu *et al.* 2013) will have a significant impact on the flow. Hydraulic characteristics of the ice cover compound channels with vegetation growing on the floodplains need to be further studied. Hydraulic characteristics have a great influence on the distribution of sediment and pollutants (Choi & Lee 2014, 2015; Zeng *et al.* 2014), and the law of sediment transport in winter also needs to be studied. The flume slope is only in 0.0005 condition, more slope conditions should be carried out in the future.

4. CONCLUSIONS

The study on the velocity distribution of a channel with compound sections has been completed, but the addition of ice cover in winter will make the hydraulic conditions of multiple cross sections more complicated. In this paper, the fluid equation under the complex cross section of ice cover is solved by integral solution along water depth. The Darcy-Weisbach friction factor is creatively unified into the sum of the two components of channel bed and ice cover, which is more conducive to the solution of the formula. The main results of this paper are as follows:

(1) Two-stage section channel with ice cover can better slow down the flow velocity in the channel, increase the retention time of water flow, and is more conducive to retaining sediment and nutrients.
(2) According to the equation, the analytical solution of transverse velocity distribution in the two-stage section channel with ice cover is solved. The model has high accuracy, and the analytical solution of velocity also provides a research basis for the distribution of sediment and phosphorus in the two-stage section channel with ice cover, and provides a theoretical reference for the design of the two-stage section channel with ice cover in the future.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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