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A laboratory and numerical study of transverse momentum exchange in vegetated channels

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ABSTRACT: Transverse exchange processes of mass and momentum in floodplain regions of channels are of primary importance regarding the sediment transport and riverbank stability. The presence of large horizontal coherent structures (LHCSs) at the interface of the floodplain and main channel regions may contribute up to 90% the amount of transverse momentum exchange between these areas. Although many momentum exchange models have been proposed and developed, their applicability in different circumstances is still unclear as their validity is usually restricted to a narrowly ranging experiment data set. In order to obtain more insight, two unique laboratory experiments of a shallow flow field in a floodplain channel with and without vegetation have been conducted. One small scale experiment was conducted at the TU Delft Water Lab. Another large-scale experiment of floodplain vegetated channel has been conducted at the Korea Institute of Civil Engineering and Building Technology - River Experiment Center (KICT-REC). The experimental data has been used to verify state-of-the-art momentum exchange models. As the limitations of these models were analyzed, a new eddy viscosity model based on the occurrence of LHCSs was proposed and validated using a variety of experimental data sets. A numerical model mimicking physical models was constructed. The experimental results were compared with the numerical results, showing the capacity of the new eddy viscosity model. Furthermore, the experimental results confirm the presence of LHCSs in a large-scale experiment. The LHCSs have the length of about 15m, which is one order of magnitude larger than that observed in the small-scale experiment.

Keywords: Vegetated channel, experiment, large coherent structures, numerical model

1 INTRODUCTION

The presence of vortex structures at the interface of the low flow and fast flow region plays an important role in the transverse exchange of momentum (Proust & Nikora 2020, Truong et al. 2019, van Prooijen et al. 2005, White & Nepf 2007). These vortex structures caused by the Kelvin-Helmholtz instability are usually large compared to the water depths and termed as large horizontal coherent structures (LHCSs). In a floodplain vegetated channel, these LHCSs have been identified as one of the main sources of the transverse momentum exchange between the vegetation region and open channel flow region (Truong & Uijttewaal 2019). As

they move along the vegetation-open channel interface, the LHCSs generate cycloid flow events composing of the flow toward the floodplain region (sweeps), the flow toward the open channel region (ejections), and the flow which are driven by the increased local pressure (stagnant and the reverse flows) (Truong et al. 2019). Consequently, these events divide the shallow flow field of the channel into different regions that are driven by different factors and have different length scales (see Figure 1a).

In between the uniform region inside the floodplain (region I) and the uniform region in the main channel (region IV) is the mixing layer (regions III and IV). The LHCSs governing the mixing layer (see Figure 1b and c) are the key factors determining the transverse exchange of momentum between the open regions (II, IV) and the vegetated regions (I, III). It is suggested that at the edge of the floodplain vegetated region, Reynolds Shear stresses (RSs) induced by LHCSs contribute more than 90% to the total turbulent shear stress (Truong & Uijtewaal 2019).

In order to properly model the transportation of sediments and nutrients within and surrounding the vegetation area, it is required to model the transverse exchange of momentum accurately. In other words, the term $\frac{1}{\rho} \frac{\partial n D \langle T_{xy} \rangle_d}{\partial y}$ which accounts for the transverse exchange of

Figure 1. Representative mean streamwise velocity (a), Reynold shear stresses (b), Large Horizontal Coherent Structures captured from the PIV measurements (c) of a compound vegetated channel (d). $Q = 45 \text{ L s}^{-1}$, $H = 12 \text{ cm}$ (Truong et al. 2019).

streamwise momentum between the open channel and the vegetated regions is the most significant term that needs to be modelled (van Prooijen et al. 2005; Truong et al. 2019). Where n is porosity, ρ is mass density, $D = D(y)$ is the water depth and $\langle T_{xy} \rangle_d$ is the sum of depth, time and space averaged transverse shear stress.

The averaged Reynolds shear stress modeled by the eddy viscosity concept is usually assumed to account for the total momentum exchange:

$$\langle \overline{T_{xy}} \rangle_d \approx -\rho \langle \overline{u'v'} \rangle_d = \nu_t \frac{d\langle \overline{u} \rangle_d}{dy} \quad (1)$$

In this way, the determination of the transverse exchange of momentum is replaced by the finding of a proper eddy viscosity model (ν_t). Several analytical models of momentum exchange considered LHCSs have been developed (Nadaoka & Yagi 1998, Nezu & Onitsuka 2001, Tamai et al. 1986, Uijttewaal & Booij 2000, van Prooijen et al. 2005, White & Nepf 2008, Xiaohui & Li 2002). However, these momentum models are usually limited due to incomplete understanding of the LHCSs, their associated flow events. Furthermore, the applicable capability of those models for different scenarios is usually restricted to a specific data set. For example, the transverse momentum exchange model of van Prooijen et al. (2005) was proposed based on an experiment of a compound channel without vegetation ($Cda = 0$), or the transverse momentum exchange model of White and Nepf (2008) was proposed based on an experiment of a vegetated channel without floodplain region ($D = const$). As a consequence, while the former cannot capture the significant reduction in the turbulent length scale in scenarios with vegetation, the latter cannot include the effects of depth variation due to floodplain region (Truong & Uijttewaal, 2019).

In this study, a new hybrid momentum exchange model (ν_t), including the physics of LHCSs that can be applied for different scenarios, was briefly introduced. This model was validated using a variety of different experimental data sets, including partially vegetated channels, vegetated floodplain channels, or compound channels without vegetation. Furthermore, the hybrid eddy viscosity model could be used as a turbulent model representing the large-scale structures in a numerical simulation of compound channel flow with vegetation to enhance the model results.

2 METHODOLOGIES

Different experimental data sets of transverse momentum exchange were collected including three representative experimental cases of White & Nepf (2007) in partially vegetated channels, the experimental results of Lambert & Sellin (1996), and the data set of Ervine et al. (2000) for compound channels without vegetation. Furthermore, a small-scale experiment of a compound channel without vegetation on the floodplain region was conducted in the laboratory of Delft University of Technology (Figure 2a). Additionally, another large-scale experiment of a compound channel without vegetation has been conducted at the Korea Institute of Construction and Building Technology - River Experiment Centre, (KICT-REC), South of Korea (Figure 2b).

The main data set is the time-series data of the streamwise velocity $U(y)$ and lateral velocity $V(y)$ along the cross-section. The velocity was measured using a Nortek Acoustic Doppler Velocity meter (ADV) at a sampling rate of 25 Hz. Velocity measurements were taken over a time interval of 10 minutes in order to achieve representative statistical data. In order to study a velocity profile over the cross-section, at least 10 points were measured at mid-depth in the region with changed water depth (transition slope). Mid-depth measurements mean that the distance from the measurement point to the bed varies with flow depth across the lateral profile.

Figure 2. Schematic view of the cross-section of the small-scale physical model (a), and large scale physical model (b). Not to scale.

Figure 3. Representative comparison of transverse momentum exchange between the measurement data (T_{xy} measured), eddy viscosity model of White & Nepf (2008) (T_{xy2}), and the new hybrid eddy viscosity model (T_{xy1}).

The hybrid eddy viscosity model was then analytically proposed and validated using different small-scale experimental data sets (Figure 3). It has been validated with large-scale experimental data sets and imposed into a numerical model to enhance the simulation results (Figure 5).

3 RESULTS

The hybrid eddy viscosity model was proposed by following footprints of the effective eddy viscosity model of van Prooijen et al. (2005) and the concept of the eddy viscosity model inside the cylinder arrays given by Kean & Smith (2013) (Truong & Uijtewaal 2019). The total eddy viscosity can be calculated according to the equation:

$$v_t = \begin{cases} \alpha \sqrt{c_f} \langle \bar{u} \rangle_d D + \frac{D_m}{D(y)} D_r^2 \beta^2 \delta^2 \left| \frac{d\langle \bar{u} \rangle_d}{dy} \right| & (y > 0) \\ \underbrace{\alpha \sqrt{c_f} \langle \bar{u} \rangle_d D}_{\text{Elder}} + \underbrace{\frac{1}{8} C_t^{-2} C_d d \langle \bar{u} \rangle_d}_{\text{vegetation drag}} + \underbrace{\frac{D_m}{D(y)} D_r^2 \beta^2 \delta^2 \left| \frac{d\langle \bar{u} \rangle_d}{dy} \right|}_{\text{LHCSs}} & (y \leq 0) \end{cases} \quad (2)$$

In which α is a constant of the order of 0.1. D_m is the mean water depth; $D(y)$ is local water depth; $D_m = \frac{D_c + D_f}{2}$; D_c is water depth in the channel, D_f is water depth in the floodplain channel. C_t is a constant of proportionality, $C_t = 1$; C_d is the drag coefficient of a single stem, $C_d = 1$. β is a proportionality constant, and δ is the mixing length.

The measured and collected data include the Reynolds shear stresses ($-\langle u'v' \rangle_d$), the measured momentum transfer is determined by:

$$T_{xy\text{measure}} = -\rho \cdot \langle u'v' \rangle_d. \quad (3)$$

The theoretical eddy viscosity model (v_t) was determined from equation (2). The transverse shear stresses based on the hybrid eddy viscosity model (T_{xy1}) were determined using:

$$T_{xy1} = -\rho \cdot v_t \cdot \frac{\partial U}{\partial y}. \quad (4)$$

The transverse shear stresses were also determined from the vortex based model of White & Nepf (2008) (T_{xy2}) in scenarios with vegetation. Figure 3 illustrates the representative validation and comparison of the transverse momentum exchange determined from the different eddy viscosity models for the scenario of vegetated floodplain and partially vegetated channel. It is suggested that the model of White & Nepf (2008) generates a relatively good result of the transverse momentum exchange between the vegetated region and open channel region. However, the peak of the lateral momentum transfer is likely to be overestimated. The results suggest that the depth-averaged transverse momentum exchange determined from the hybrid eddy viscosity model can be made to fit with different experimental data sets with an average value of 0.0625 (Truong & Uijtewaal 2019).

The numerical model can be run first with traditional eddy viscosity models such as Elder formulation. Based on the simulation results, the presence of LHCSs can be checked, and the shear-layer width can be determined. Figure 4 illustrates the comparison between the numerical model and the physical model regarding the presence of the LHCSs. It is shown that the LHCSs can be resolved in the numerical model. The pattern of the LHCSs resolved by the numerical model is comparable with that captured by the tracers from the physical model.

In terms of practical engineering applications, one of the most challenging tasks of the utilization of a depth-averaged two dimensional in the horizontal model (2DH model) is to provide an adequate model of turbulent viscosity. This turbulent closure model needs to represent different complicated hydrodynamic phenomena such as the horizontal mixing or the bed generated turbulence. As the applicability of the hybrid eddy viscosity model has been demonstrated, it can be imposed in a numerical model of compound channels to enhance the numerical results. Figure 5 illustrates a comparison for the mean streamwise velocity between

Figure 4. Representative comparisons of the pattern of the LHCSs between the numerical model (vorticity fields) (left panel) and the small-scale physical model (right panel).

Figure 5. Representative comparison of the depth averaged velocity between the numerical model included hybrid eddy viscosity and the physical model (small-scale experiment).

the physical and numerical models in which the hybrid eddy viscosity was used. It can be seen that there is a good agreement between the experimental results and the numerical results.

It is noted that as the LHCSs move along the floodplain-channel interface, they generate fluctuations in the time signal of the mean transverse velocities. These fluctuations appear to be strongest at the floodplain edge (Truong & Uijttewaai 2019). Figure 6 shows the time series of fluctuated lateral velocity v'^+ at the of floodplain-open channel interface in the small-scale experiment (a) and large-scale experiment (b) of the compound channel. The water depth in the floodplain is about 6 cm and 25 cm in small-scale and large-scale experiments, respectively. The results indicate significant differences in the LHCSs in the small-scale and large-scale experiments. The presence of LHCSs is more pronounced in the large-scale experiment than in a small-scale experiment. In the large scale experiment, there are LHCSs with a period of about 30 s, while in the small scale experiment, the LHCSs move with a period of about 7.5 s. Assuming that these LHCSs move with the mean streamwise velocity at the floodplain edge (20 cm s^{-1} and 50 cm s^{-1} in the small-scale and large-scale experiment, respectively). In this context, the LHCSs appeared in the large-scale experiment have a length of about 15 m, which is one order of magnitude larger than that in the small-scale experiment (about 1.5 m).

Figure 6. Representative time series of the fluctuated lateral velocity v' at the edge of floodplain in compound channel without vegetation, in small scale experiment (a), and large scale experiment (b).

The application of the hybrid eddy viscosity model has been considered. Future works will focus on understanding these LHCSs in the large scale experiment. The hybrid eddy viscosity model would be validated using large scale experimental data sets (with a different transition slope).

4 CONCLUSIONS

The presence of LHCSs and their associated flow events at the interface of low flow and fast flow regions play a significant factor, governing the transverse momentum exchange processes between these two regions. It is necessary to have the right model of transverse momentum exchange before determining the exchange of mass *e.g.* sediments and nutrients. As the limitation of the most up-to-date momentum exchange models was reviewed, a hybrid eddy viscosity model based on the LHCSs was briefly introduced. Two experiments have been conducted at different scales to obtain more data sets of the transverse momentum exchange. The hybrid eddy viscosity model could be validated using a variety of different data sets. The results show the applicability of the new eddy viscosity model for different scenarios, including the partially vegetated channel, or compound channel with and without vegetation. For practical engineering applications, the new eddy viscosity model could be imposed into a numerical model to improve the numerical results. Furthermore, the experimental results indicate the presence of LHCSs in a large-scale experiment. The length of these LHCSs is one order of magnitude larger than that observed in the small-scale experiment.

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