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A Laboratory Study of the Shallow Flow Field in a Vegetated Compound Channel

S. H. Truong, K. L. Phan, Marcel J. F. Stive and W. S. J. Uijttewaal

Abstract The significant defensive role of vegetation in general and mangroves in particular for coastal and estuarine regions has been increasingly recognized. However, understanding the shallow flow field in and around the region of vegetation is still limited. In order to gain more insight, a laboratory experiment of a vegetated compound channel was conducted. The emerged circular cylinders are a representative model for the emergent mangrove forest. Scenarios of different widths and densities of vegetation were considered. Data acquired from Acoustic Doppler Velocimetry (ADV) and force sensors have been analysed. The influences of vegetation on the shallow flow field were clarified by comparing different scenarios with and without vegetation. Furthermore, the results confirm the presence of the large horizontal coherent structures (LHCSs). The large coherent structures formed in the mixing layer at the vegetation interface emerge, promoting the transverse momentum exchange toward the forests. The LHCSs has not only boosted flow penetration into the vegetated floodplain area but also strongly disturbed the flow inside the forest. As the LHCSs move, they cause the fluctuation of the force on the cylinders. The fluctuations are largest at the vegetation edge. Negative values of stream wise forces were also recorded.

Keywords Vegetation · Laboratory study · Turbulent flow · Forces on vegetation · Compound vegetated channel

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1 Introduction

Vegetation in general and mangroves in particular play an important role for the protection of coastal and estuarine regions. The complex systems of strong and dense mangrove roots, stems and canopies provide an effective tool to damping the attacking waves and the strong currents along banks. In recent decades, this topic has withdrawn increasingly more attention, especially in the context of increasing coastal and river bank erosion and sea level rise.

Numerous studies, mostly based on experimental results have been published, focusing on understanding the hydrodynamic processes in and around forests and the defensive role of vegetation in coastal and estuarine regions (Ikeda et al. 1991; Nadaoka and Yagi 1998; Nezu and Onitsuka 2001; Van Prooijen et al. 2005; White and Nepf 2007, 2008). However, the knowledge obtained is limited. For example, what is the required forest width to avoid the squeeze effect and to ensure a sustainable protection and development? it is not clear to what distance the mangrove forest should be remained so that their sustainable development can be ensured.

Along the Mekong Delta Estuary, mangrove forests usually dominate the floodplain region with a gentle slope of 1:10. In the last three decades they have been strongly destroyed because of the construction of fish-farms in this region. As a result, only a narrow strip of mangrove of about 50 to 100 m is usually left, and river banks are eroding with the rate of about 3 myr^{-1} (see Fig. 1). In this condition, the estuarine mangroves can be studied as vegetation in a floodplain channel (Truong

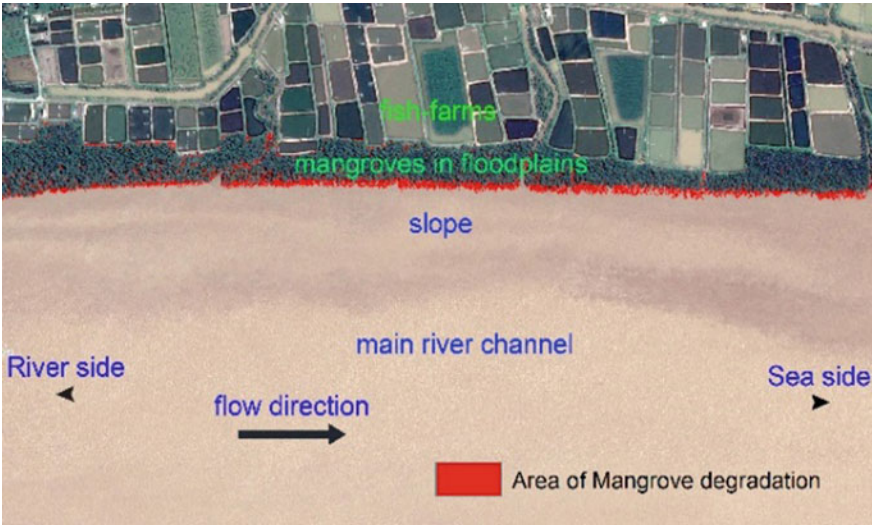

Fig. 1 Representative mangrove distribution along the dai estuary in the mekong delta

et al. 2019; Truong et al. 2017) in which, the hydrodynamics in and around the vegetation is the key factor determining the sustainable growth of the whole ecological system.

2 Experimental Set-up and Measurement

In order to obtain more insight in this topic, a physical model, mimicking the estuarine mangrove in the Mekong Delta Estuary was set up and performed in scenarios with different mangrove densities, discharge and water levels. The top view of the experiment can be seen in Fig. 2.

The experiment profile includes a floodplain, a transition slope (1:10) and an open flow channel. Cylinder arrays was installed in the floodplain area. The density of cylinder arrays was determined based on the solid volume fraction of *S. Alba*,

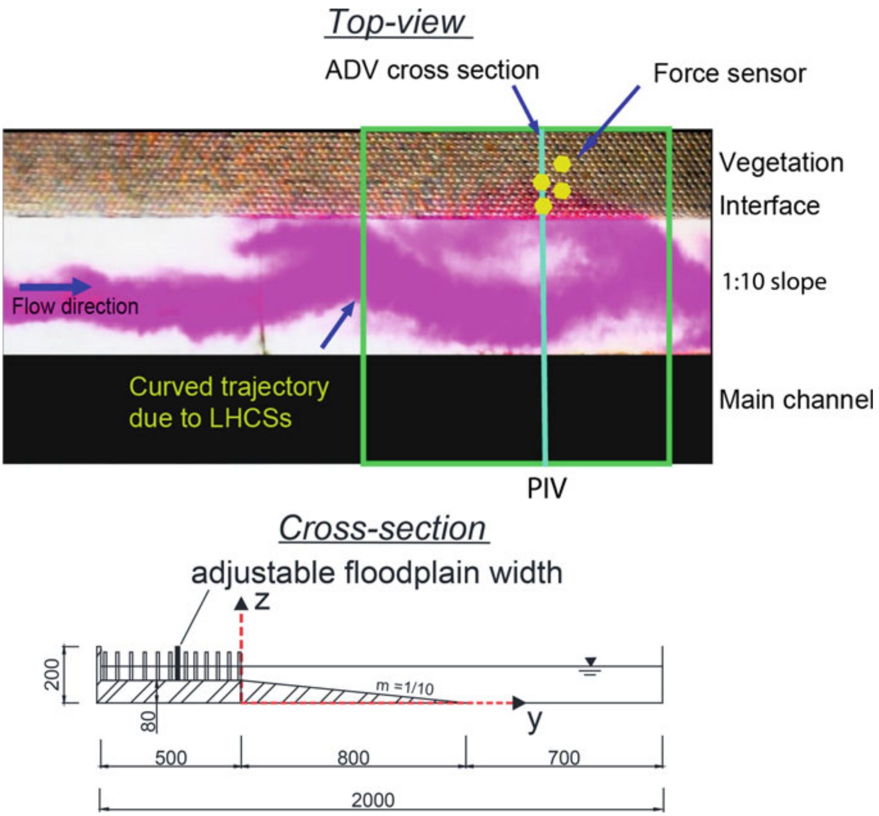

Fig. 2 Experimental set-up including top view and cross section of the experiment and measured techniques

which is the typical type of mangroves along the Mekong estuarine (Truong et al. 2017). In this way, two densities of cylinder arrays (139 and 556 cylinder/m^2) were considered. The input discharge and the water level could be changed by means of a pump upstream and a downstream crested weir, respectively.

It is noted that the flow over the shallower floodplain is much slower than in the deeper main channel because of the water depth difference inside the vegetation and adjacent open channel. Consequently, a mixing layer develops between the vegetated floodplain and the channel. In the present experiment, the measurements were taken at 10 m from the beginning of the flume, where the mixing layer can be safely assumed to be fully developed.

A Nortek Acoustic Doppler Velocity meter (ADV) was used to measure the depth-averaged velocity (mid-depth). The quality of the ADV signal was significantly improved by an electrolyzer with 0.1 mm thick wires placed in front of the ADV (see Fig. 3). Moreover, four sensitive force sensors were mounted under the bottom of the metal cylinders located at different locations inside the vegetation region. In this way, the direct streamwise force on a single cylinder can be obtained and the drag coefficient can be determined.

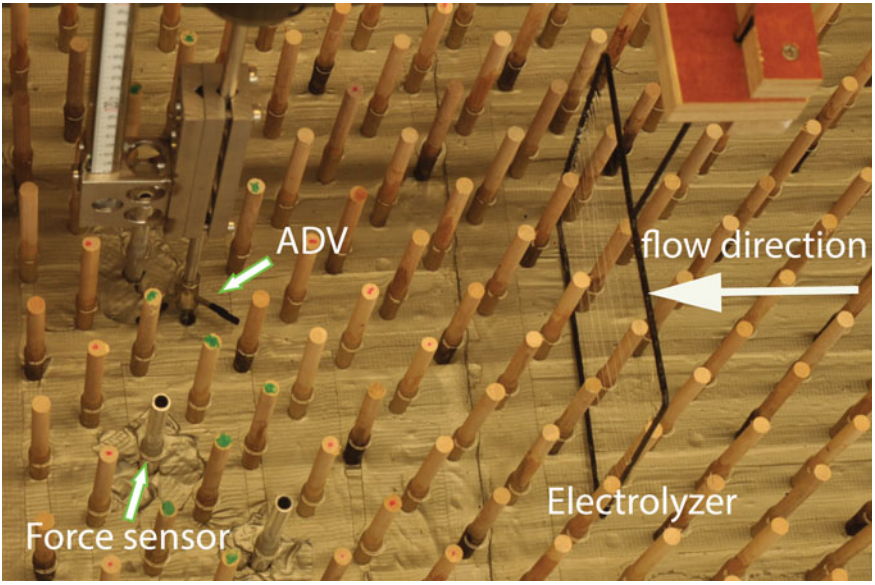

Fig. 3 Velocities and forces measurement

3 Mean Stream Wise Velocity

Velocity measurements were taken over a time interval of 10 min (sampling rate of 25 Hz). After that, it was time-averaged to obtain the depth and time-averaged velocity at the corresponding location. Figure 4 illustrates the representative velocity profile in scenarios with different cylinder densities (floodplain width = 50 cm; discharge = 80 l/s; water depth = 14 cm).

First, it can be clearly observed that for the cases with vegetation, the depth and time-averaged streamwise velocity inside the floodplain region was damped significantly (about 2 and 8 cm/s in dense and sparse cases compared to 35 cm/s in cases without vegetation). As a result, in the cases with vegetation, the velocity gradient between the vegetation area and the main open channel greatly increases. Furthermore, it can be seen that the profile of the mean streamwise velocity in the dense case can decrease and reach an uniform value in the floodplain region after a distance of about 10 cm (Fig. 4). In other words, the penetration of the flow into the cylinder arrays is about 10 cm. It is noticed that this penetration of the flow into the vegetation region appears to be larger than that in cases with sparse vegetation

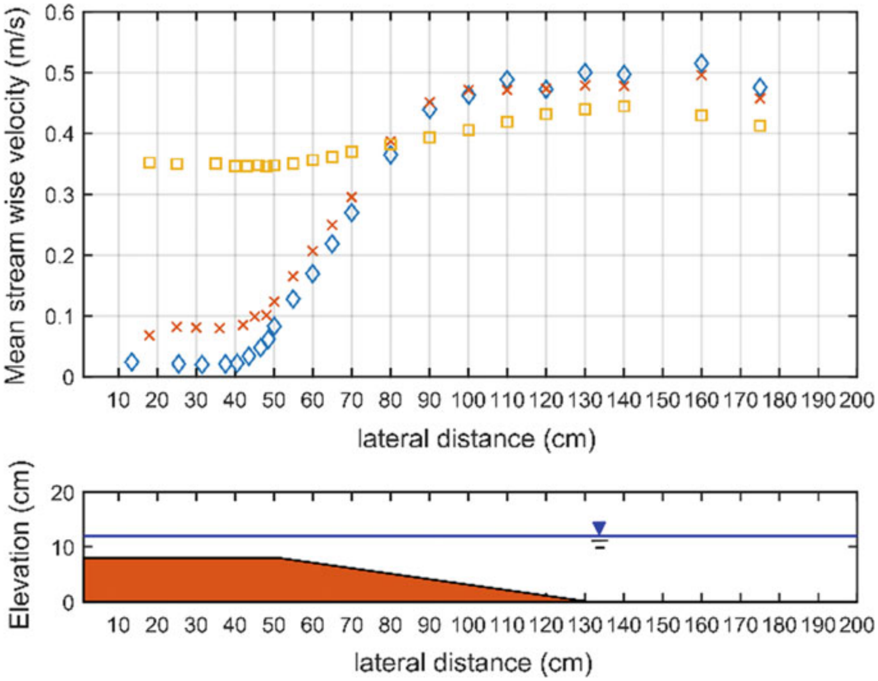

Fig. 4 Mean streamwise velocity in scenarios with different densities (squares: no cylinder; crosses: sparse density; rhombuses: high density), floodplain width = 50 cm; discharge = 80 l/s; water depth = 14 cm

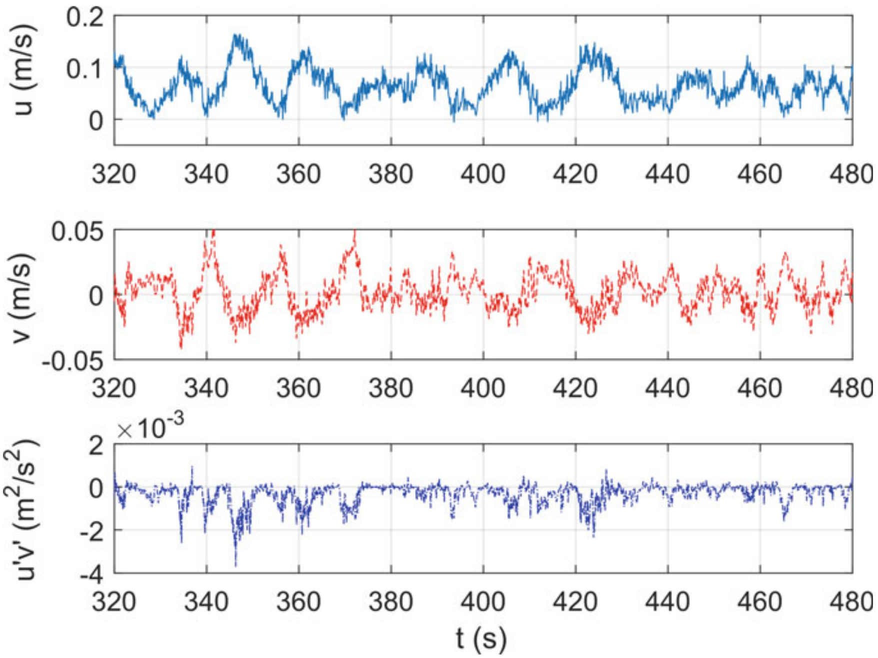

Fig. 5 Mean streamwise and transverse velocities and the corresponding Reynold's stresses at the vegetation interface, in a scenario with floodplain width = 50 cm; discharge = 80 l/s; water depth = 14 cm

and in cases without vegetation. In this sense, the presence of vegetation appears to boost the flow penetration into the vegetated floodplain area.

In order to obtain further insight, the data measured from the ADV can be analysed in more detail. Figure 5 shows the time series of the mean streamwise velocities (u), lateral velocities (v) and their corresponding shear stresses (u' v') which were obtained from the ADV at the vegetation interface.

First, it can be clearly seen that there is a fluctuation in the time signal of the streamwise (u) and transverse velocity (v) (period T = 15–20 s). This is caused by the presence of quasi-two dimensional structures which is termed large horizontal coherent structures (LHCSs). In the literature, these large coherent structures were recognized because of the Kelvin-Helmholtz (K-H) instability triggered by the parallel shear flows between the floodplain and adjacent open region (Bousmar 2002; White and Nepf 2008; Adrian and Marusic 2012).

The peaks in the corresponding turbulence shear stresses (u' v') can also be observed. These peaks are associated with the flow events i.e. sweeps and ejections (White and Nepf 2018). As the transverse exchange of momentum is directly related to the Reynold shear stresses, these flow events are of primary importance for the exchange processes in the vegetation (Truong et al. 2019).

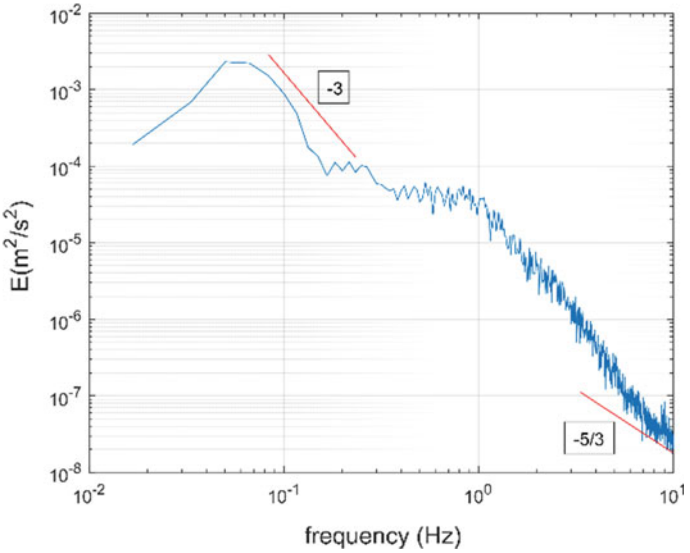

Fig. 6 Power density spectra of lateral velocity fluctuations at location 46.5 cm distance from the wall—dense scenario, 50 cm width, discharge = 45 l/s, water level = 12 cm

4 Power Density Spectra (PDSs)

The presence of LHCSs can be studied in more detail by analysing the power density spectra (PDSs) of the fluctuating transverse velocity (v') (Figs. 6 and 7). The quasi-two dimensional eddy structures can be recognized through the −3 slope at the low-frequency side of the PDS (Uijttewaal and Booij 2000). The decrease in energy density at the high-frequency side of the PDSs almost follows a slope −5/3 which is indicative of flows with a large inertial subrange.

Figure 7 shows the PDS of the lateral velocity fluctuations along the cross-section of the flume in cases with different floodplain widths (50 and 25 cm). In the main channel, the −3 slope at the low-frequency side of the PDSs cannot be observed. Moreover, when reducing the floodplain width from 50 to 25 cm, clear differences in the PSDs can be observed. The definite peak regions (yellow regions) in the power density spectrum with slope −3 in case 25 cm is more spread and less concentrated as in cases of 50 cm floodplain width. This implies that the LHCSs are less regular when the floodplain width is reduced.

5 Forces Induced by the LHCSs

As the LHCSs move they causes the velocity fluctuation, resulting in the fluctuation of the forces. Figure 8a shows the distribution of measured stem forces by box plots

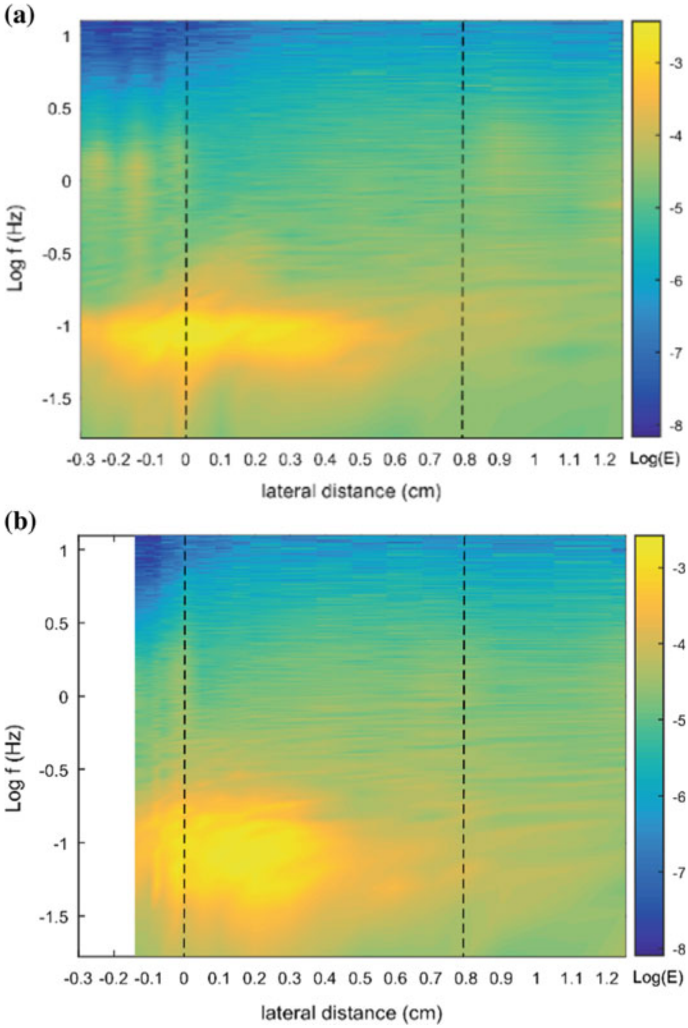

Fig. 7 Power density spectra of lateral velocity fluctuations along the cross-section of the flume, dense scenario, 50 cm width (**a**) and 25 cm width (**b**), discharge = 45 l/s, water level = 12 cm

at different locations. The mean value is given by red line with the box indicating the 25th and 75th percentiles. The fluctuation is strongest at the floodplain edge (location 4). Because the effects of LHCSs become weaker further inside the vegetation, the fluctuation and the magnitude of the streamwise forces also become smaller. It is noticed that the negative values of the streamwise forces can be observed in this figure. This is possibly caused by the backward motions induced by the LHCs (Truong et al. 2019).

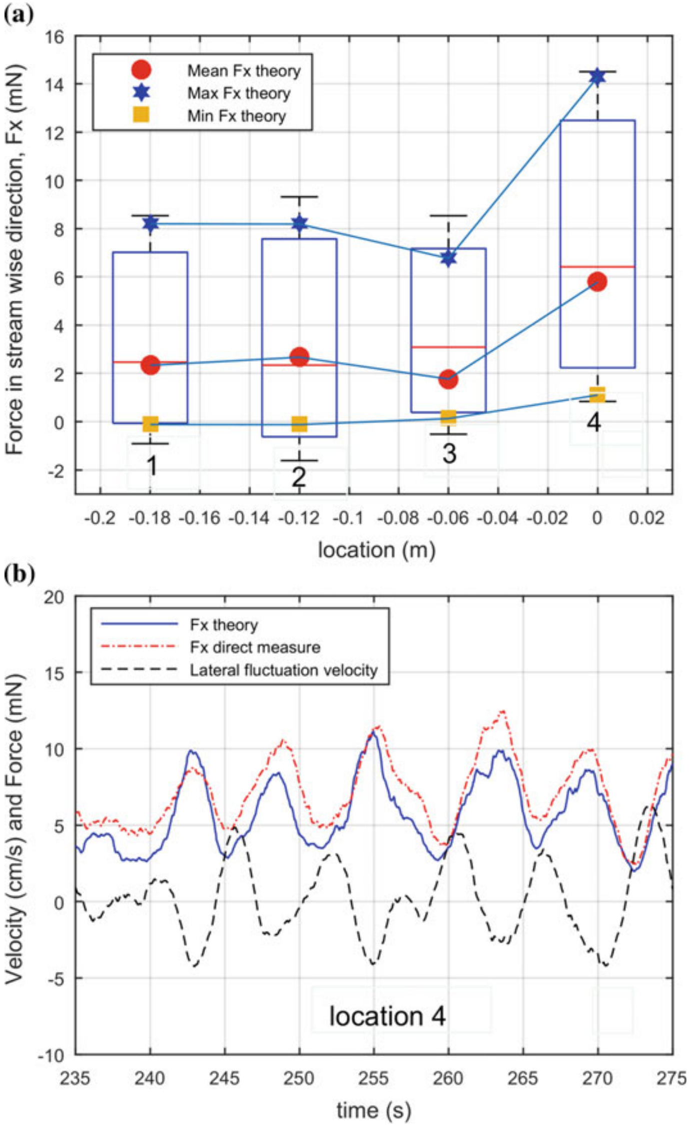

Fig. 8 Distribution of measured stem forces on cylinders, including the corresponding values determined from the theory (**a**). Directly measured streamwise force, F_x on cylinder 4 (at the edge of the vegetation), compared with the estimated forces, $F_{x,theory}$ from the theory (Cd = 1; correlation 55%) and corresponding lateral velocity fluctuation (**b**)

Figure 8b shows the time series of the streamwise force (F_x) measured on cylinder 4 together with the predicted one ($F_{x,theory}$) and the lateral fluctuation velocity (v'). It is suggested that the force reaches its maximum value together with the minimum lateral fluctuation velocity ($v' < 0$). This indicates that the force on the cylinder is largest during the inflows (sweeps) and smallest during the outflows (ejections).

6 Conclusions

This chapter introduces some initial results of a laboratory experiment of a vegetated floodplain channel, mimicking the estuarine mangrove forests in the Mekong Delta, Vietnam. The experimental results confirm the capability of the vegetation in damping the flow inside the forests. The presence of vegetation significantly increases the velocity gradient, boosting the development of the LHCSs, and thereby also causes more mixing into the vegetation. The LHCSs then creates flow events, contributing a large part to the total transverse momentum exchange. These flow events cause velocity fluctuations. As a result, the forces acting on the vegetation also fluctuate and apparently reach the maximum values during the ejections. Future work will focus on a further interpretation of the data acquired and the validation of a numerical model using the experimental data.

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