

## Copyright Undertaking

This thesis is protected by copyright, with all rights reserved.

**By reading and using the thesis, the reader understands and agrees to the following terms:**

1. The reader will abide by the rules and legal ordinances governing copyright regarding the use of the thesis.
2. The reader will use the thesis for the purpose of research or private study only and not for distribution or further reproduction or any other purpose.
3. The reader agrees to indemnify and hold the University harmless from and against any loss, damage, cost, liability or expenses arising from copyright infringement or unauthorized usage.

### IMPORTANT

If you have reasons to believe that any materials in this thesis are deemed not suitable to be distributed in this form, or a copyright owner having difficulty with the material being included in our database, please contact [lbsys@polyu.edu.hk](mailto:lbsys@polyu.edu.hk) providing details. The Library will look into your claim and consider taking remedial action upon receipt of the written requests.

EXPERIMENTAL STUDY ON FLOW STRUCTURE AND  
BEDFORM DEVELOPMENT IN OPEN CHANNEL WITH  
VEGETATION PATCH

YUANHENG ZHANG

PhD

The Hong Kong Polytechnic University

2026



The Hong Kong Polytechnic University

Department of Civil and Environmental Engineering

Experimental Study on Flow Structure and Bedform  
Development in Open Channel with Vegetation Patch

Yuanheng Zhang

A thesis submitted in partial fulfilment of the requirements for the  
degree of Doctor of Philosophy

August 2025

# CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgment has been made in the text.

\_\_\_\_\_ (Signed)

Yuanheng Zhang  
\_\_\_\_\_ (Name of student)

# Abstract

Aquatic vegetation is a critical component in coastal and riverine ecosystems, forming important wetland and littoral habitat. The presence of vegetation introduces additional hydraulic resistance, which reduces flow velocity. This tends to enhance sediment deposition and sediment retention, which can maintain bed stability and promote the growth of ridges and islands. Conversely, vegetation also generates turbulence, facilitating sediment resuspension, leading to erosion and reduction of bed elevation. Changes to the bedform can in turn affect the flow dynamics and the continued growth of aquatic plants. These dynamic feedback mechanisms complicate predictions of how vegetation distribution impacts sediment retention and river morphology. Unfortunately, during the past decades, vegetation has been removed or lost from rivers, deltas and lakes, due to natural causes and agricultural and industrial land-use. To restore and manage aquatic vegetation ecosystems, a comprehensive understanding of the interactions among flow, vegetation, and sediment transport is therefore essential.

This thesis investigates the complex interplay between aquatic vegetation, flow dynamics, and sediment transport through a series of laboratory experiments and analyses. The main contributions and key findings are as follows:

1. Patch elongation and wake structure: For an in-stream emergent vegetation patch, patch elongation influences the wake structure by adjusting the bleed flow velocity deficit as well as triggering the Kelvin-Helmholtz vortices along the lateral edges of the patch. Wake von Karman vortex street, unable to be triggered under a low patch density, however, can be generated by patch elongation. Meanwhile, Kelvin-Helmholtz vortex streets are triggered along the two patch lateral edges, re-increasing the in-patch velocity and imposing contributions to the wake vortex streets generation. Specially, the initiation of the patch-edge Kelvin-Helmholtz vortex may accelerate the steady wake velocity, shorten the steady wake length and decay the energy of the wake vortex.
2. Flow confinement and shear layer interaction: In channels with symmetrical vegetation patches, the lateral extension of the array confines the shear layer, reducing its penetration from a fully developed thickness to half the width of the open region. This confinement occurs when the shear layers grow to the channel centerline before becoming fully developed, influenced by the shear layer initiated at the opposite array. Despite the shear

layer being confined to half width of the open region and the time-averaged shear stress being zero at the centerline, the shear-layer vortices interact across the open region, producing significant turbulent events at the centerline with equal contributions from both sides. Furthermore, a wave motion occurs with a phase shift of  $\pi$  radians between the parallel vortex streets. The alternating vortex cores between the parallel vortex streets amplify the pressure gradient, intensifying coherent structures and facilitating momentum exchange across the channel centerline. As the blockage ratio increases, vortex size decreases, convection velocity increases, and vortex frequency rises. Although the turbulent intensity is enhanced, the decreased resident time for turbulent flow events may result in a shorter transport distance. Overall, the shear layer that develops on one interface acts as an additional resistance to shear turbulence on the other interface.

3. Flow structure and morphological changes: To connect flow structure and morphological changes in and around a rectangular vegetation patch. The emergent patch was constructed in an 8-cm sand bed. Near the leading edge of the patch, enhanced turbulence levels produced sediment erosion. Some of the eroded sediment was carried into the patch, forming an interior deposition dune. The denser patch resulted in a smaller dune due to stronger lateral flow diversion and weaker interior streamwise velocity. After the leading-edge dune, in the fully developed region of the patch, vortices formed in the shear-layers along the patch lateral edges. Elevated turbulence at the patch edge produced local erosion. For the dense patch, material eroded from the edge was transported into the patch to form a flow-parallel ridge, and there was no net sediment loss/gain by the patch. For the sparse patch, material eroded from the edge was transported away from the patch, resulting in a net loss of sediment from the patch. In the wake of both patches, deposition occurred near the wake edges and not at the wake centerline, which was attributed to the weak lateral transport associated with the weakness of the von Karman vortex street. Specifically, the lateral transport length-scale was less than the half width of the patch. The increasing bedform height within the wake progressively weakened and narrowed the von Karman vortex street, illustrating an important feedback from morphological evolution to the flow structure. Despite significant local sediment redistribution, the patch did not induce channel-scale sediment transport.

In summary, this thesis offers fundamental insights into the mechanics of the interactions among aquatic plants, flow dynamics, and sediment transport, focusing on flow structure formation and interaction, and their resulting bedform development. The theoretical insights contribute to developing more reliable approaches to the restoration and management of aquatic ecosystems, ultimately enhancing ecosystem resilience, promoting biodiversity, and ensuring the long-term sustainability of aquatic environments. The main findings, insufficiencies, and recommendations for the whole study are summarized at the end of this thesis.

# Publications Arising from the Thesis

## Journal paper

- **Zhang, Y. H.**, Duan, H. F., Yan, X. F., & Stocchino, A. (2023). Experimental study on the combined effects of patch density and elongation on wake structure behind a rectangular porous patch. *Journal of Fluid Mechanics*, 959, A36.
- **Zhang, Y. H.**, Duan, H. F., Yan, X. F., & Stocchino, A. (2024). Quantifying wake dynamics subjected to stream vegetation patch elongation: The influence of patch-edge vortices. *Physics of Fluids*, 36(5).
- **Zhang, Y. H.**, Stocchino, A., & Duan, H. F. (2025). Development and interaction of Kelvin-Helmholtz vortices along two parallel fringing vegetation arrays. *Journal of Fluid Mechanics*, 1019, A7.
- **Zhang, Y. H.** & Nepf, H. (2025). Morphological change within and around a rectangular array of emergent vegetation is linked to flow structure. *Journal of Fluid Mechanics*, 1018, A37.
- Ma, Y. **Zhang, Y. H.**, Duan, H. F. (2025). Three-dimensional flow structures through submerged vegetation patches with uniform and non-uniform stem spacing in an open channel. *Physics of Fluids*, 37 (7).
- Yan, X. F., Duan, H. F., **Zhang, Y. H.**, & Wang, X. K. (2023). Momentum fluxes across multiple mixing interfaces subject to partially-distributed submerged canopy flows. *Journal of Hydrology*, 622, 129742.

## Conference presentation

- **Zhang, Y. H.**, Yan, X. F., Wang, X. K., Duan, H. F. On the initiation and evolution of von Karman vortex behind rectangular vegetation patches with different aspect ratios and densities. *presented in the 14th International Symposium on Ecohydraulics. Nanjing, China, 2022*

- **Zhang, Y. H.**, Duan, H. F., Yan, X. F. Formation and structure of wake flows after a rectangular vegetation patch in open channel. *presented in the 40th IAHR World Congress, 2023. Rivers-Connecting Mountains and Coasts. Vienna, Austria, 2023.*
- **Zhang, Y. H.**, Duan, H. F. Experimental study on the Kelvin-Helmholtz vortex generation and development in vegetated channel flows. *presented in the 2023 International Symposium on Sustainable Urban Drainage. Jiashan, Zhejiang, China.*
- **Zhang, Y. H.**, Duan, H. F., Yan, X. F., Stocchino, A. Vortex formation and interaction within and around an elongated vegetation patch. *presented in The 4th International Symposium of Water Disaster Mitigation and Water Environment Regulation (WDWE2024) cum The 14th South China Sea Tsunami Workshop (SCSTW-14). Hong Kong, China, 2024.*
- **Zhang, Y. H.**, Duan, H. F. The blocking effect of parallel fringing vegetation arrays on flow structure. *presented in 41st IAHR World Congress, 2025. Innovative Water Engineering for Sustainable Development. Singapore, 2025.*

# Acknowledgements

First and foremost, I would like to express my deepest gratitude to my Chief supervisor, Professor Huan-Feng Duan, for his invaluable guidance, encouragement, and support throughout my doctoral studies. His expertise, patience, and insightful feedback have been instrumental in shaping both this thesis and my academic development.

I would also like to sincerely thank Professor Alessandro Stocchino, for his continuous support, constructive advice, and encouragement during my research. His valuable input has greatly contributed to the completion of this work.

I would like to extend my heartfelt thanks to my host supervisor, Professor Heidi Nepf, during my attachment at Massachusetts Institute of Technology. Her warm welcome, professional guidance, and generous support provided me with a valuable international research experience and broadened my academic horizons.

I am also grateful to the members of my thesis committee, Professor Mingfu Guan and Professor Sung-Uk Choi for their constructive comments and suggestions, which have significantly improved the quality of my research.

Special thanks go to the technicians in our laboratory, especially Mr. Kwok-Hing Leung, for his technical assistance, patience, and dedication. His support was essential for the successful completion of my experiments.

I had the great pleasure of working with my fellows and friends who helped, inspired and encouraged me during my Ph.D. study, including but not limited to, James Vincent Brice, Qiuru Chen, Na Chen, Annalisa De Leo, Tianan Deng, Shuo Hao, Zijian Hu, Yuanyuan Jia, Ernie In Him Lee, Mingxi Li, Fei Li, Yanshan Li, Zhengyang Li, Yinghong Lin, Shimeng Liu, Zhiyong Long, Xuanwen Liang, Yuan Ma, Bin Pan, Hyoungchul Park, Liying Qiu, Abbasali Rahmani, Bingjie Ren, Husnain Tansar, Ulises Torres-Herrera, Vincent Tjuatja, Mnali Wang, Yilin Wu, Hui Yang, Fangping Xu, Xiaotong Xu, Ying Zhang, Tian Zhao, Yunhai Zheng, Xiaosheng Zhu (in the alphabetic order).

The completion of my thesis would not have been possible without the financial support from Hong Kong Research Grants Council (RGC) under Project No. C5002-22Y and NSFC/RGC Joint Research Scheme under Project. No. N.PolyU559/22. I gratefully acknowledge Research Student Attachment Programme (RSAP) and PolyU PhD Scholars International Collaborative

Research Fellowship (ICRF) for providing the financial support for my research visit.

Last but not least, I am deeply grateful to my parents for their unconditional love, understanding, and encouragement. Their support has been my greatest source of strength throughout this journey. A very special thank goes to my love, Dr. An Li, for his unwavering love, patience, and support.

Thank you all.



# Contents

|          |                                                         |           |
|----------|---------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                     | <b>1</b>  |
| 1.1      | Significance and Values . . . . .                       | 1         |
| 1.2      | Objectives . . . . .                                    | 4         |
| 1.3      | Outline of the thesis . . . . .                         | 4         |
| <b>2</b> | <b>Literature review</b>                                | <b>7</b>  |
| 2.1      | Interaction between vegetation and water flow . . . . . | 7         |
| 2.1.1    | Stem-scale structure . . . . .                          | 7         |
| 2.1.2    | Flow adjustment and distribution . . . . .              | 9         |
| 2.1.3    | Flow structure in submerged vegetation patch . . . . .  | 14        |
| 2.1.4    | Flow through and around patch of finite width . . . . . | 17        |
| 2.1.5    | Wake structure . . . . .                                | 22        |
| 2.2      | Sediment transport in vegetated channel . . . . .       | 28        |
| 2.2.1    | Incipient sediment motion . . . . .                     | 28        |
| 2.2.2    | Sediment transport rate . . . . .                       | 30        |
| 2.3      | Sediment pattern in vegetated channels . . . . .        | 32        |
| 2.3.1    | Net deposition pattern in rigid bed . . . . .           | 33        |
| 2.3.2    | Bedform development in mobile bed . . . . .             | 37        |
| 2.3.3    | The flow response to the morphological change . . . . . | 42        |
| <b>3</b> | <b>Theory and experiment setup</b>                      | <b>45</b> |
| 3.1      | Theory . . . . .                                        | 45        |
| 3.1.1    | Governing equations . . . . .                           | 45        |
| 3.1.2    | Velocity adjustment . . . . .                           | 46        |
| 3.1.3    | Shear layer penetration . . . . .                       | 48        |
| 3.1.4    | Vortex frequency . . . . .                              | 50        |
| 3.2      | Rigid-bed experiments . . . . .                         | 50        |
| 3.3      | Mobile-bed experiments . . . . .                        | 52        |
| 3.4      | Vegetation patch . . . . .                              | 53        |

|          |                                                                                                                                       |            |
|----------|---------------------------------------------------------------------------------------------------------------------------------------|------------|
| 3.5      | Flow and bedform measurement . . . . .                                                                                                | 54         |
| 3.6      | Data treatment . . . . .                                                                                                              | 62         |
| 3.7      | Dye visualization . . . . .                                                                                                           | 62         |
| <b>4</b> | <b>The combined effects of patch density and length-to-width aspect ratio on wake structure behind a rectangular vegetation patch</b> | <b>68</b>  |
| 4.1      | Introduction . . . . .                                                                                                                | 68         |
| 4.2      | Materials and Methods . . . . .                                                                                                       | 70         |
| 4.3      | Results . . . . .                                                                                                                     | 74         |
| 4.3.1    | Hydrodynamic adjustment . . . . .                                                                                                     | 74         |
| 4.3.2    | Wake vortex structure . . . . .                                                                                                       | 79         |
| 4.4      | Discussion . . . . .                                                                                                                  | 82         |
| 4.4.1    | Wake structure related to patch density and aspect ratio . . . . .                                                                    | 82         |
| 4.4.2    | Coexistence between KH vortex street and wake vortex street . . . . .                                                                 | 84         |
| 4.4.3    | Wake vortex street formation thresholds . . . . .                                                                                     | 86         |
| 4.5      | Summary . . . . .                                                                                                                     | 93         |
| <b>5</b> | <b>The influence of patch-edge vortices on wake dynamics</b>                                                                          | <b>95</b>  |
| 5.1      | Introduction . . . . .                                                                                                                | 95         |
| 5.2      | Materials and Methods . . . . .                                                                                                       | 95         |
| 5.3      | Results and Discussions . . . . .                                                                                                     | 96         |
| 5.3.1    | Bleed flow deficit related to cumulative hydraulic resistance . . . . .                                                               | 96         |
| 5.3.2    | Patch-edge KH coherent structure . . . . .                                                                                            | 97         |
| 5.3.3    | The contribution of the patch-edge KH vortex to wake structure . . . . .                                                              | 100        |
| 5.4      | Summary . . . . .                                                                                                                     | 105        |
| <b>6</b> | <b>Development and interaction of Kelvin-Helmholtz vortices along two parallel fringing vegetation arrays</b>                         | <b>106</b> |
| 6.1      | Introduction . . . . .                                                                                                                | 106        |
| 6.2      | Materials and Methods . . . . .                                                                                                       | 109        |
| 6.3      | Results . . . . .                                                                                                                     | 113        |
| 6.3.1    | Flow adjustment and shear layer evolution . . . . .                                                                                   | 113        |
| 6.3.2    | Vortex formation and interaction . . . . .                                                                                            | 121        |
| 6.4      | Discussion . . . . .                                                                                                                  | 128        |
| 6.4.1    | Wave response . . . . .                                                                                                               | 128        |
| 6.4.2    | Instantaneous fields at water surface . . . . .                                                                                       | 133        |
| 6.4.3    | Quadrant analysis . . . . .                                                                                                           | 134        |
| 6.4.4    | Momentum transport . . . . .                                                                                                          | 142        |

|          |                                                                                                                                                       |            |
|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| 6.5      | Summary . . . . .                                                                                                                                     | 145        |
| <b>7</b> | <b>The interaction between the patch-scale coherent structures associated with a rectangular array of emergent vegetation and bedform development</b> | <b>148</b> |
| 7.1      | Introduction . . . . .                                                                                                                                | 148        |
| 7.2      | Methods . . . . .                                                                                                                                     | 148        |
| 7.3      | Results . . . . .                                                                                                                                     | 150        |
| 7.3.1    | Velocity and bedform evolution through the patch . . . . .                                                                                            | 150        |
| 7.3.2    | The formation of the flow parallel depositional ridge deposition . . . . .                                                                            | 156        |
| 7.3.3    | The influence of stem diameter on interfacial shear layer . . . . .                                                                                   | 157        |
| 7.3.4    | Deposition in the patch wakes . . . . .                                                                                                               | 159        |
| 7.3.5    | Feedback from morphological evolution to wake velocity structure . . . . .                                                                            | 161        |
| 7.4      | Discussion . . . . .                                                                                                                                  | 163        |
| 7.4.1    | The decay of wake vortex with bed form evolution . . . . .                                                                                            | 163        |
| 7.4.2    | Vortex frequency alignment . . . . .                                                                                                                  | 166        |
| 7.5      | Summary . . . . .                                                                                                                                     | 168        |
| <b>8</b> | <b>Conclusions, limitations, and future works</b>                                                                                                     | <b>170</b> |
| 8.1      | Conclusions . . . . .                                                                                                                                 | 170        |
| 8.2      | Limitations and future work . . . . .                                                                                                                 | 172        |
| <b>A</b> | <b>Summary of experimental parameters.</b>                                                                                                            | <b>208</b> |

# List of Figures

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |    |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.1 | Aquatic vegetation in Walden Pond. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 3  |
| 1.2 | The outline of the thesis. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 6  |
| 2.1 | Turbulent eddies of characteristic size $l$ produced in an array of cylinders with uniform stem diameter $d$ and average distance to the nearest neighboring stem $\Delta S$ . (a) Sparse array: eddy size is governed by the cylinder diameter, i.e., $l \sim d$ . (b) Dense array: eddy size is governed by the cylinder spacing, i.e., $l \sim \Delta S$ . This figure is modified from Tanino & Nepf (2008b). . . . .                                                                                                                                                                                                  | 8  |
| 2.2 | Conceptual diagram for flow adjustment for an instream emergent vegetation patch the corresponding streamwise velocity adjustment along the patch center-line. This figure is adapted from Rominger & Nepf (2011). $L_i$ is the interior adjustment length. Low-flow blockage regime corresponds to $C_{Dab} < 2$ and high-flow blockage regime corresponds to $C_{Dab} \geq 2$ . . . . .                                                                                                                                                                                                                                  | 11 |
| 2.3 | The flow structure and vertical distribution of streamwise velocity for submerged vegetation patch. $H$ is the patch height. (a) For sparse regime ( $aH < 0.1$ ), the velocity follows a rough boundary-layer profile. (b) For intermediate regime ( $0.1 \leq aH < 0.23$ ), shear structure at the top of the patch induces patch-scale turbulence, which penetrates a distance of $\delta_e$ into the patch. (c) For dense regime ( $aH > 0.23$ ), $\delta_e < H$ , the bed remains insulated from patch-scale turbulence and is dominated by stem-scale turbulence. This figure is adapted from Nepf (2012a) . . . . . | 15 |
| 2.4 | Vegetation behaviors with increasing Cauchy number $Ca$ . Strongly reconfigured vegetation behaves as a rigid body, thereby suppressing the formation of Kelvin–Helmholtz vortices (d). This figure is adapted from Okamoto et al. (2016). . . . .                                                                                                                                                                                                                                                                                                                                                                         | 18 |
| 2.5 | The horizontal shear structure formed at the lateral interface(s) of (a) along-bank and (b) in-channel emergent vegetation patch. $b$ is the width for the along-bank patch, but the half width for the in-channel patch. $U_1$ and $U_2$ are the lowest velocity within the vegetation patch and highest velocity adjacent to the patch, respectively. $\delta_l$ is the penetration of the shear layer into the patch and $\delta_o$ is the thickness of the shear layer in the bare channel. . . . .                                                                                                                    | 20 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.6  | The flow structure of (a) sole along-patch vortices at the lateral interface of the array in unconfined conditions; (b) alternating along-patch and along-wall vortices in confined conditions. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 21 |
| 2.7  | The formation of secondary flow near lateral interface of a submerged array partially obstructed the channel, leading to S-shaped vertical velocity profile of streamwise velocity near the lateral interface. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 22 |
| 2.8  | Wake behaviors behind an circular vegetation patch. Dashed circle indicates the boundary of the patch. (a) Coupled individual wake, where patch-scale shear layers are stable and the patch wake is dominated by individual element-scale wakes. (b) KH instability wake, where patch-scale shear layers are susceptible to KH instability, but do not generate von Karman vortex street. (c) ‘Steady+shedding’ wake, where a steady wake region presents before the development of a von Karman vortex street. (d) Vortex street wake, where a von Karman vortex street is initiated immediately behind the patch. This figure is adapted from Nicolle & Eames (2011), He, Ghisalberti, An, Draper, Branson, Ren & Cheng (2024). . . . .                                                                                                                   | 24 |
| 2.9  | (a) Top view and (b) side view of the flow structure behind a submerged, circular patch. $D$ is the diameter of the patch. $H$ is the patch height. (a) shows the flow structure when the wake is dominated by the horizontal vortices, $H > D$ . (b) shows the domination of the vertical vortices in the wake, $H < D$ . This figure is adapted from Hu et al. (2018). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 27 |
| 2.10 | Sediment flux to an along-bank emergent vegetation patch. The suspended particle concentration $C(x,y)$ is normalized by the upstream concentration $C_0$ . $x_D$ is diverging region in the vegetation patch. $x_a$ is the advection length scale. $b$ is the width of the vegetation patch. $\delta_v$ is penetration thickness of the shear layer into the patch, in which the particle concentration is the same as the free stream, $C_0$ . $\delta_{\max}$ is the diffusion length scale, which is defined as the maximum distance particles can be delivered from the streamwise interface by lateral dispersion. (a) Simulated suspended particle concentration in the vegetation patch at $x > x_D$ . (b) Simulated lateral concentration profiles across the patch width ( $0 < y < b$ ). This figure is adapted from Zong & Nepf (2011). . . . . | 36 |
| 2.11 | (a) A side view of longitudinal bed elevation associated with a vegetation patch. (b) A front view of lateral bed elevation associated with a finite vegetation patch, with a patch width smaller than the channel width. The dashed line indicates the bed elevation before exposure to the water flow. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 39 |
| 2.12 | The upwelling flow at the back of the cylinder in deformed bed. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 43 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |    |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.1 | (a) The mesh screens at the upstream inlet of the flume and the tailgate at the downstream end of the channel. (b) The top view of the rigid-bed flume. . . . .                                                                                                                                                                                                                                                                                                                                                | 51 |
| 3.2 | The lateral distribution of time-averaged streamwise velocity ( $\bar{u}$ ) measured upstream of the patch confirmed the laterally uniform conditions. $x = 0$ is the leading edge of the patch. $y = 0$ is the centerline of the patch and channel. The dashed line indicates the mean upstream velocity, $U_\infty$ . . . . .                                                                                                                                                                                | 52 |
| 3.3 | Sediment return and dowels installed upstream of the test section. The tall dowels are used to dissipate the energy caused by the water drop. The short dowels are used to smooth the incoming flow. . . . .                                                                                                                                                                                                                                                                                                   | 53 |
| 3.4 | Bedform observed upstream of the vegetation array. In this region, the velocity was not affected by the presence of vegetation patch, suggesting that the incoming velocity was below the critical threshold necessary to initiate sediment movement, thereby maintaining a flat bed. . . . .                                                                                                                                                                                                                  | 54 |
| 3.5 | Convergence test confirmed that the 120 s sampling duration was sufficient. Here, cumulatively averaged velocity ( $\bar{u}$ and $\bar{v}$ ), root-mean-square of the fluctuating velocity ( $u_{rms}$ and $v_{rms}$ ), turbulent kinetic energy ( $k_t$ ), horizontal shear stress ( $-\overline{u'v'}$ ) are plotted against accumulated sample number. The sampling frequency was (a) 75 Hz in rigid-bed test, (b) 200 Hz in mobile-bed test. All averages converged within 20000 sample points. . . . .    | 56 |
| 3.6 | A unit cell. The velocity measured at the midpoint between four dowels (denoted by black circle) was within 11% of the spatially averaged velocity measured by five positions within the unit cell, including four corners and one center point (denoted by 'x'). . . . .                                                                                                                                                                                                                                      | 57 |
| 3.7 | Vertical profiles of time-averaged (a) streamwise velocity ( $\bar{u}$ ) and turbulent kinetic energy ( $k_t$ ), and (b) transverse velocity ( $\bar{v}$ ) and Reynolds shear stress ( $-\overline{u'v'}$ ). $\bar{u}_d$ is the depth-averaged streamwise velocity. Because the profiles are vertically uniform, the time-mean and turbulent velocity characteristics collected at mid-depth can reasonably represent the depth-average, and the flow can be considered approximately two-dimensional. . . . . | 57 |
| 3.8 | Lateral profiles for (a) bed elevation ( $\delta_b$ ), (b) time-averaged streamwise velocity ( $\bar{u}$ ), (c) turbulent kinetic energy ( $k_t$ ), (d) horizontal shear stress ( $-\overline{u'v'}$ ) and (e) the root-mean-square of the fluctuating spanwise velocity ( $v_{rms}$ ). The dashed line indicates the lateral interface of the patch. The flow structure and morphological changes were mostly symmetric across the centerline of the array and channel ( $y = 0$ ). . . . .                   | 58 |
| 3.9 | The experimental setup for Particle Image Velocimetry (PIV) analysis from (a) side view and (b) top view. . . . .                                                                                                                                                                                                                                                                                                                                                                                              | 59 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                      |    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.10 | Panoramic view after merging process of the four camera acquisitions: during (a) calibration, (b) image acquisitions, in which the darker regions indicate the vegetated arrays with less particles. . . . .                                                                                                                                                                                                         | 60 |
| 3.11 | Comparison of lateral profiles of time-averaged streamwise velocity ( $\bar{u}$ ) in the fully developed region, measured at the middle of water depth using ADV and at the water surface using PIV. The dashed lines indicate the interfaces of the vegetation arrays. . . . .                                                                                                                                      | 60 |
| 3.12 | Convergence test for PIV analysis confirmed that the 40 s sampling duration was sufficient. Here, cumulatively averaged velocity ( $\bar{u}$ and $\bar{v}$ ), root-mean-square of the fluctuating velocity ( $u_{rms}$ and $v_{rms}$ ), turbulent kinetic energy ( $k_t$ ), horizontal shear stress ( $-\overline{u'v'}$ ) are plotted against accumulated sampling time. The sampling frequency was 100 Hz. . . . . | 61 |
| 3.13 | Comparison of vortex frequencies collected at the middle of water depth by ADV and on the water surface by PIV. The dashed line is a 1:1 ratio. . . . .                                                                                                                                                                                                                                                              | 61 |
| 3.14 | Data treatment. The example velocity data was collected behind a high-density vegetation patch with a small time-averaged velocity and high turbulence. Filtered data refers to the data in which records with a correlation coefficient below 70% were removed. Despiked data refers to velocity records from which spikes were removed using the method developed by Goring & Nikora (2002). . . . .               | 63 |
| 3.15 | Dye visualization experiment on rigid bed. Flow is from top to bottom (red arrow). The dye was injected near the corners of the trailing edge. The yellow lines mark 20 cm intervals in both $x$ and $y$ directions (yellow arrows). The white arrows indicates the steady wake length ( $L_{d1}$ ). . . . .                                                                                                         | 65 |
| 3.16 | Dye visualization of Kelvin-Helmholtz (KH) vortices initiated at the lateral edges of an instream vegetation array on a mobile bed, observed at different running time: (a) $t = 0$ , (b) $t = 96$ hr. Dye was released approximately 1.5 m upstream of the trailing edge of the patch, where KH vortices were observed to be well-organized. . . . .                                                                | 66 |
| 3.17 | The estimation of Karman vortex shedding period, $T_d$ . . . . .                                                                                                                                                                                                                                                                                                                                                     | 66 |
| 3.18 | Comparison of vortex frequencies observed in the wake (von Karman vortex, labeled as 'VK' in the figure) and near the side edge (Kelvin-Helmholtz vortices, labeled as 'KH' in the figure), as extracted from video ( $f_{dye}$ ) and from power spectral density ( $f_{PSD}$ ). The dashed line is a 1:1 ratio. The figure confirms that the $f_{dye}$ was consistent with $f_{PSD}$ . . . . .                      | 67 |
| 4.1  | Conceptual diagram for flow structure near the vegetation patch (top) and the streamwise velocity adjustment along the patch centerline (bottom). . . . .                                                                                                                                                                                                                                                            | 69 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.2  | Experimental setup. (a) Top view. Patch configuration and dye injection points, longitudinal and lateral transects (dashed lines) of velocity measurements. (b) Side view. Velocity measurements were conducted at the middle of the water depth. . . . .                                                                                                                                                                                                                                        | 72 |
| 4.3  | Dye visualization experiment. The impact of (a) solid volume fraction for $L/W = 2.22$ . (b) patch elongation for $\Phi = 0.013$ . Flow is from top to bottom (red arrow). The dye was injected near the corners of the trailing edge. The yellow lines mark 20 cm intervals in both $x$ - and $y$ -direction (yellow arrows). The white arrows indicates the steady wake length ( $L_{d1}$ ). . . . .                                                                                           | 73 |
| 4.4  | Longitudinal profiles of velocity for patches under the same length (a) $L = 0.1$ m, (b) $L = 0.2$ m, (c) $L = 0.6$ m, (d) $L = 1.0$ m, (e) $L = 1.40$ m. The dashed lines indicate the trailing edges of the patches. The longitudinal velocity is measured at the patch centerline, $y = 0$ . . . . .                                                                                                                                                                                          | 75 |
| 4.5  | Longitudinal profiles of velocity for patches under the same $\Phi$ (a) Case A ( $\Phi = 0.009$ ), (b) Case B ( $\Phi = 0.013$ ), (c) Case Bw ( $\Phi = 0.013$ ), (d) Case C ( $\Phi = 0.020$ ), (e) Case D ( $\Phi = 0.040$ ). The dashed lines with corresponding color of the case indicate the trailing edges of the patches with $L = 0.10$ m, $0.20$ m, $0.60$ m, $1.0$ m, $1.4$ m from left to right. The longitudinal velocity is measured along the patch centerline, $y = 0$ . . . . . | 76 |
| 4.6  | Comparison between $L_{i,c}$ and $L_{i,m}$ . The dashed lines indicated the 80% confidence intervals. . . . .                                                                                                                                                                                                                                                                                                                                                                                    | 77 |
| 4.7  | Lateral profiles of $\bar{u}/U_\infty$ for (a) Case A ( $\Phi = 0.009$ ), (b) Case D ( $\Phi = 0.040$ ) at $x = L + L_1$ . Owing to the symmetry about the centerline ( $y/W = 0$ ), measurements were only made on one side of the flume ( $0 < y/W < 2.56$ ). The black dashed line shows the patch edge. . . . .                                                                                                                                                                              | 79 |
| 4.8  | Lateral profiles of normalized Reynolds stress $-\overline{u'v'}/u_*^2$ for (a) Case B ( $\Phi = 0.013$ ), (b) Case D ( $\Phi = 0.040$ ) at $x = L + L_1$ . The black dashed line shows the patch edge. . . . .                                                                                                                                                                                                                                                                                  | 80 |
| 4.9  | Comparison between $L_1$ and $L_{d1}$ . $L_1$ is the length of steady wake measured from the longitudinal profile of $\bar{u}$ at the patch centerline. $L_{d1}$ is measured from dye images, and defined as the point at which the dye traces meet at the centerline. The dashed lines indicated the 80% confidence intervals. . . . .                                                                                                                                                          | 81 |
| 4.10 | Power spectra ( $S_{vv}$ ) along the patch centerline ( $y = 0$ ). The dashed lines indicate the leading edge and trailing edge of the patch. Note: the width ( $W$ ) of Cases Bw = $0.21$ m, Cases A $\sim$ D = $0.09$ m. . . . .                                                                                                                                                                                                                                                               | 83 |



|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.11 | The impact of $\Phi$ (left) and aspect ratio ( $L/W$ , right) on (a) normalized steady wake length, $L_1/W$ , (b) normalized steady wake velocity, $U_1/U_\infty$ , (c) wake recovery rate, $(U_\infty - U_1)/L_2$ , (d) wake recovery length, $L_2$ . . . . .                                                                                                                                                                                                                                                                        | 85  |
| 4.12 | Power spectra ( $S_{vv}$ ) along the lateral edge of the patch ( $x = 0 \sim L, y = W/2$ ). The dashed lines indicate the interior adjustment region ( $L_i$ ). Note: the width ( $W$ ) of Cases Bw = 0.21 m, Cases A ~ D = 0.09 m. . . . .                                                                                                                                                                                                                                                                                           | 87  |
| 4.13 | Comparison between $f_{VK}$ and $f_{KH}$ . $f_{VK}$ is the frequency of von Karman vortex and $f_{KH}$ is the frequency of KH instability. Both are measured from velocity power spectra. The solid line indicates $f_{VK} = f_{KH}$ and the dashed lines indicates the 80% confidence intervals. . . . .                                                                                                                                                                                                                             | 88  |
| 4.14 | Normalized Reynolds stress at the position of $(x, y) = (L, W/2)$ . The dashed line indicates the threshold value for normalized Reynolds stress of the presence of KH vortex. “VK” indicates wake vortex street; “KH” indicates KH vortex street; “Y” indicates yes/presence; “N” indicates no/absence. . . . .                                                                                                                                                                                                                      | 88  |
| 4.15 | Velocity difference (a) $U_1/U_2$ ; (b) $(U_2 - U_1)/U_\infty$ at $x = L + L_1$ versus aspect ratio ( $L/W$ ). The shaded area indicates the absence of wake vortex street according to the threshold value. . . . .                                                                                                                                                                                                                                                                                                                  | 90  |
| 4.16 | Velocity difference (a) $U_{e1}/U_{e2}$ ; (b) $(U_{e2} - U_{e1})/U_\infty$ at $x = L$ versus aspect ratio ( $L/W$ ). The shaded area indicates the absence of wake vortex street according to the threshold value. . . . .                                                                                                                                                                                                                                                                                                            | 91  |
| 4.17 | Aspect ratio ( $L/W$ ) versus solid volume fraction ( $\Phi$ ). The shaded area indicates the absence of vortex street according to the threshold value. . . . .                                                                                                                                                                                                                                                                                                                                                                      | 92  |
| 5.1  | The relationship between the bleed flow adjustment, $(U_{e2} - U_{e1})/U_\infty$ , and (a) patch density, $\Phi$ , shifted by $L/W$ for clarity; (b) patch aspect ratio, $L/W$ , shifted by $\Phi$ for clarity. The dashed lines with corresponding color for each case indicate the general trend of the measured data. (c) The relationship between $(U_{e2} - U_{e1})/U_\infty$ and cumulative hydraulic resistance, $\Phi L/W$ . The dashed line indicates Eq. 5.5, with a coefficient of determination, $R^2 = 0.75$ . . . . .   | 98  |
| 5.2  | The initiation and evolution of the patch-scale KH vortex at the end of the patch side edge, i.e., $(x, y) = (L, W/2)$ at different values of $L/W$ under varying $\Phi$ , evaluated by the (a) power spectra density ( $S_{vv}$ ), with a horizontal dashed line indicating the natural frequency for a free shear layer, $f\theta/U = 0.032$ ; and (b) autocorrelation ( $R_{vv}$ ) of the spanwise velocity. The vertical dashed line indicates the threshold value of $L/W$ for the initiation of the patch-edge KH vortex. . . . | 99  |
| 5.3  | Indicator for the patch-edge KH vortex initiation and normalized Reynolds stress at the position of $(x, y) = (L, W/2)$ : (a) velocity shear, $(U_{e2} - U_{e1})/(U_{e2} + U_{e1})$ , and (b) velocity difference along with aspect ratio, $(L/W)(U_{e2} - U_{e1})/U_\infty$ . . . . .                                                                                                                                                                                                                                                | 100 |

|     |                                                                                                                                                                                                                                                                                                                                                                   |     |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.4 | The impact of the patch's cumulative hydraulic resistance ( $\Phi L/W$ ) on (a) the normalized steady wake velocity, $U_1/U_\infty$ , (b) the normalized steady wake length, $L_1/\sqrt{A}$ , and (c) the normalized energy of the wake vortex, $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ . . . . .                                                                      | 101 |
| 5.5 | The impact of the lateral velocity gradient, normalized by channel width, $(U_{e2} - U_{e1})/U_\infty/(W/B)$ , on (a) the normalized steady wake velocity, $U_1/U_\infty$ , (b) the normalized steady wake length, $L_1/\sqrt{A}$ , and (c) the normalized energy of the wake vortex, $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ . . . . .                                | 103 |
| 5.6 | The impact of the patch-edge KH vortex on (a) the normalized steady wake velocity, $U_1/U_\infty$ , (b) the normalized steady wake length, $L_1/\sqrt{A}$ , and (c) the normalized energy of the wake vortex, $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ . . . . .                                                                                                        | 104 |
| 6.1 | Conceptual diagram for flow structure in a symmetrical vegetation-channel-vegetation system. Near the leading edge of the patch, the flow is diverted laterally out of the array over an adjustment length. Shear layers form along each flow-parallel interface, which produce vortices by Kelvin-Helmholtz instability. . . . .                                 | 107 |
| 6.2 | Aquatic vegetation distributed on both sides of the natural rivers with a high flow blockage. Picture was taken at Dasha River in Shenzhen, China. . . . .                                                                                                                                                                                                        | 109 |
| 6.3 | The laboratory setup. (a) Top view: illustration of the model array and dye injection points, longitudinal and lateral transects (red dashed lines) of velocity measurements by ADV. (b) Front view: velocity measurements were conducted at the mid-depth. The streamwise and lateral coordinates and velocities are $(x, u)$ and $(y, v)$ respectively. . . . . | 110 |
| 6.4 | The lateral profiles of the time-average lateral velocity ( $\bar{v}$ ) at (a) upstream region, and (b) fully developed region for all scenarios. . . . .                                                                                                                                                                                                         | 112 |
| 6.5 | The longitudinal profiles of the velocity shear across the lateral interface, $\lambda = (U_2 - U_1)/(U_2 + U_1)$ , under (a) varying array densities for $2b/B = 0.47$ , and (b) varying array widths for $\Phi = 2.0\%$ . . . . .                                                                                                                               | 114 |
| 6.6 | The evolution of shear structure indicated by the lateral velocity gradient ( $d\bar{u}/dy$ ), under varying array density for $2b/B = 0.47$ . The black lines indicate the edge of the shear layer with a threshold value of $d\bar{u}/dy = 0.1s^{-1}$ . The dashed line indicate the channel centerline and the edge of the vegetated zones. . . . .            | 115 |
| 6.7 | The development of shear structure indicated by the lateral velocity gradient ( $d\bar{u}/dy$ ), under varying blockage ratios for $\Phi = 1.3\%$ . The black lines indicate the edge of the shear layer with a threshold value of $d\bar{u}/dy = 0.1s^{-1}$ . The dashed line indicate the channel centerline and the edge of the vegetated zones. . . . .       | 116 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.8  | The influence of array density ( $\Phi$ ) on the (a) velocity redistribution ( $\bar{u}/U_o$ ) and (b) normalized shear stress ( $-\overline{u'v'}/u_{*,b}^2$ ). Data was collected at fully developed region for cases with $2b/B = 0.40$ . The dashed line indicates the lateral interface of the array. Here, $u_{*,b}$ is the bed friction velocity. . . . .                                                                                                                                                                                                       | 117 |
| 6.9  | The lateral profiles of the (a) normalized time-average streamwise velocity ( $\bar{u}/U_o$ ), and (b) normalized shear stress ( $-\overline{u'v'}/u_{*,b}^2$ ), under varying blockage ratios ( $2b/B$ ). Data was collected at fully developed region for cases with $\Phi = 2.0\%$ . The dashed lines (with corresponding color of the case) indicate the lateral interface of the array. $u_{*,b}$ is the bed friction velocity. . . . .                                                                                                                           | 118 |
| 6.10 | Interfacial shear stress, $u_*^2$ versus $U_2^2$ . The dashed line is fitted from data in unconfined condition ( $2b/B < 0.5$ ), $u_*^2 = 0.013U_2^2$ , with a $R^2 = 0.98$ . . . . .                                                                                                                                                                                                                                                                                                                                                                                  | 120 |
| 6.11 | (a) $u_*^2/U_1^2$ scales with $C_{Da}\delta_o$ . The dashed line is the fitted data, $u_*^2/U_1^2 = 0.02 + 0.49C_{Da}\delta_o$ , with a $R^2 = 0.83$ . (b) $U_1^2/U_2^2$ scales with $h/[C_f C_{Da}\delta_o^2]$ . The dashed line is the fitted data, $U_1^2/U_2^2 = 0.0004h/[C_f C_{Da}\delta_o^2]$ , with a $R^2 = 0.92$ . . . . .                                                                                                                                                                                                                                   | 121 |
| 6.12 | Lateral distribution of cross-power spectral density ( $S_{uv}$ ) in fully-developed region at $2b/B = 0.47$ for varying array density: (a) $\Phi = 0.9\%$ ; (b) $\Phi = 1.3\%$ ; (c) $\Phi = 2.0\%$ ; (d) $\Phi = 4.0\%$ . The vertical dashed line marks the lateral interface of the array. while the horizontal dashed line indicates the normalized natural frequency of mixing layers, $f\theta/U_c = 0.032$ (Ho & Huerre 1984). The dots indicate the peak normalized frequencies for each data collected. . . . .                                              | 123 |
| 6.13 | Lateral distribution of cross-power spectral density ( $S_{uv}$ ) in fully-developed region at $\Phi = 2.0\%$ for varying array blockage ratios: (a) $2b/B = 0.33$ ; (b) $2b/B = 0.40$ ; (c) $2b/B = 0.47$ ; (d) $2b/B = 0.53$ ; (e) $2b/B = 0.60$ ; (f) $2b/B = 0.67$ . The vertical dashed line marks the lateral interface of the array, while the horizontal dashed line indicates the normalized natural frequency of mixing layers, $f\theta/U_c = 0.032$ (Ho & Huerre 1984). The dots indicate the peak normalized frequencies for each data collected. . . . . | 124 |
| 6.14 | The impact of blockage ratio ( $2b/B$ ) on the cross-power spectral density of the streamwise and spanwise velocity ( $S_{uv}$ ) for case with $\Phi = 2.0\%$ at the channel centerline ( $y = 0$ ). . . . .                                                                                                                                                                                                                                                                                                                                                           | 125 |
| 6.15 | Patch-averaged lateral distributions of dissipation rate $\varepsilon$ ( $m^2/s^3$ ) calculated using the Smagorinsky model at the water surface: (a) for different array widths at a constant $\Phi = 1.3\%$ and (b) for different array densities at a constant $2b/B = 0.67$ . The dashed lines (with corresponding color of the case in (a) and black in (b)) indicate the lateral interfaces of the arrays. . . . .                                                                                                                                               | 126 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |     |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.16 | The impact of blockage ratio ( $2b/B$ ) on (a) vortex frequency ( $f$ ), collected at the array interface ( $y = B/2 - b$ ), (b) momentum thickness ( $\theta$ ), and (c) advection velocity ( $U_c$ ). . . . .                                                                                                                                                                                                                                                                                                                                                         | 127 |
| 6.17 | The comparisons of the integral time scales in the (a, b) streamwise direction ( $T_u$ ) and (c, d) lateral direction ( $T_v$ ) and (e, f) their ratios ( $T_u/T_v$ ) at the water surface and at middle of water depth. . . . .                                                                                                                                                                                                                                                                                                                                        | 129 |
| 6.18 | Dye visualization test. (a) The alternation of the vortex cores from either side of the two arrays creates a wave response across the main channel, under varying array density ( $\Phi$ ) at $2b/B = 0.67$ . (b) The impact of the array-to-channel blockage ratio, $2b/B$ , on vortex structure in the main channel with a $\Phi = 1.3\%$ . The yellow lines mark 10 cm intervals in both $x$ and $y$ directions. The vertical arrow indicates the flow direction. The horizontal arrows indicate the width of the array ( $b$ ) and the flume width ( $B$ ). . . . . | 131 |
| 6.19 | (a, b) Time records of fluctuating streamwise velocity, $u'(t)$ , transverse velocity, $v'(t)$ and (c, d) their corresponding phase shift at lateral edge of the array, $y = B/2 - b$ , and channel centerline, $y=0$ . The time lags between two signals were normalized by the measured vortex period. The data was collected for case with a $\Phi = 0.9\%$ and $2b/B = 0.67$ . The dashed line of 0.50 suggests a phase shift of $\pi$ radians. The dashed line of 0.25 indicates a phase shift of $\pi/2$ radians. . . . .                                         | 132 |
| 6.20 | Galilean-decomposed velocity vector fields and contour of Okubo-Weiss parameters under varying vegetation densities. The convection velocity used was 0.05 m/s. The dashed lines indicate the interfaces of the vegetated zones. . . . .                                                                                                                                                                                                                                                                                                                                | 135 |
| 6.21 | Galilean-decomposed velocity vector fields and contour of Okubo-Weiss parameters under varying blockage ratios. The convection velocity used was 0.05 m/s. The dashed lines indicate the interfaces of the vegetated zones. . . . .                                                                                                                                                                                                                                                                                                                                     | 136 |
| 6.22 | The distributions of turbulent kinetic energy ( $k_t$ ) under varying array densities. The dashed lines indicate the interfaces of the vegetated zones. . . . .                                                                                                                                                                                                                                                                                                                                                                                                         | 137 |
| 6.23 | The distributions of turbulent kinetic energy ( $k_t$ ) under varying blockage ratios. The dashed lines indicate the interfaces of the vegetated zones. . . . .                                                                                                                                                                                                                                                                                                                                                                                                         | 138 |
| 6.24 | The distributions of (a, b) fluctuating streamwise velocity ( $u_{rms}$ ) and (c, d) fluctuating lateral velocity ( $v_{rms}$ ) under varying blockage ratios. The dashed lines indicate the interfaces of the vegetated zones and the centerline of the channel. . . . .                                                                                                                                                                                                                                                                                               | 139 |
| 6.25 | The contribution of large-scale coherent structures to each flow event. The data was collected (a, b) at the lateral interface of the array and (c, d) channel centerline in the fully developed region, before ( $2b/B = 33.3\%$ ) and after ( $2b/B = 66.7\%$ ) shear layer penetrating to the centerline. The percentage at each quadrant indicates the contribution from the corresponding event. . . . .                                                                                                                                                           | 141 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.26 | The enhancement of fluctuating lateral velocity ( $v_{rms}$ ) at the channel centerline under varying blockage ratios ( $2b/B$ ), normalized by upstream fluctuating lateral velocity, $v_{rms,o}$ . . . . .                                                                                                                                                                                                                                                                                                              | 142 |
| 6.27 | Time series of (a) fluctuating streamwise velocity, $u'(t)$ , and (b) fluctuating transverse velocity, $v'(t)$ , measured at both lateral edges of the arrays, $y = \pm(B/2 - b)$ . Panels (c) and (d) show the time series of $u'(t)$ and $v'(t)$ at each lateral edge, specifically at (c) $y = B/2 - b$ and (d) $y = b - B/2$ . . . . .                                                                                                                                                                                | 143 |
| 6.28 | The lateral profile of time-averaged shear stress ( $-\overline{u'v'}$ ) averaged across the full-developed region. The dashed line indicate the lateral interfaces of the arrays.                                                                                                                                                                                                                                                                                                                                        | 143 |
| 6.29 | The influence of blockage ratio on the momentum exchange across the array interface, evaluated by (a) wave excursion length, $\Lambda$ , normalized by the array width, $b$ ; (b) Pearson correlation coefficient, $r_{uv}$ . . . . .                                                                                                                                                                                                                                                                                     | 144 |
| 7.1  | Experiment setup. (a) Top view. (b) Side view. Not to scale. The longitudinal and transverse coordinates and velocity are $(x, y)$ and $(u, v)$ , respectively. Red dashed lines indicate measurement transects, including the centerline, the flow-parallel edge, and several lateral cross-sections. . . . .                                                                                                                                                                                                            | 150 |
| 7.2  | Longitudinal profiles of (a, b) time-averaged streamwise velocity ( $\bar{u}$ ) and turbulent kinetic energy ( $k_t$ ), and (c, d) bed elevation ( $\delta_b$ ) for high flow blockage patch and low flow blockage patch, respectively. The data collected on the centerline ( $y = 0$ ). Vertical dashed lines indicate the leading ( $x = 0$ ) and trailing ( $x = L$ ) edges of the array. In (a) and (b), the horizontal dashed line indicates the estimated critical turbulence level for sediment mobility. . . . . | 152 |
| 7.3  | Net deposition ( $\delta_b$ ) for the (a) high flow blockage patch ( $C_{Dab} = 3.88$ ) with a length of $L = 265$ cm, (b) low flow blockage patch ( $C_{Dab} = 0.91$ ) with a length of $L = 265$ cm and (c) extended low flow blockage patch ( $C_{Dab} = 0.91$ ) with a length of $L = 385$ cm. Grey indicates zero net deposition; red indicates positive net deposition; blue indicates negative net deposition (net erosion). The solid rectangle indicates the limits of the array. . . . .                        | 154 |
| 7.4  | Longitudinal profiles along the flow-parallel edge at $y = b$ : (a) time-averaged spanwise velocity ( $\bar{v}$ ) and (b) fluctuating spanwise velocity ( $v_{rms}$ ). Lateral profiles of (c) time-averaged streamwise velocity ( $\bar{u}$ ) and (d) turbulent kinetic energy ( $k_t$ ) in the fully developed region ( $x > L_i$ ). . . . .                                                                                                                                                                            | 155 |

- 7.5 Conditions contributing to the formatin of edge-parallel ridge within the fully developed region ( $x > L_i$ ) of the high flow blockage patch ( $C_{Dab} = 3.88$ ). (a) Lateral profiles of time-averaged streamwise velocity ( $\bar{u}$ ) and Reynolds shear stress ( $-\overline{u'v'}$ ). (b) Magnitude of power spectral density (PSD) of cross-stream velocity ( $v$ ), shown by color bar, distributed by lateral position and frequency. The horizontal dashed line indicates expected Kelvin-Helmholtz frequency,  $f_{KH}\theta/\bar{U} = 0.032$ . The time series of fluctuating streamwise ( $u'(t)$ ) and transverse ( $v'(t)$ ) velocity (c) at 1 cm outside the patch and (d) within the patch ( $y = b - \delta_s$ ). (f) Lateral profiles of bed elevation ( $\delta_b$ ) and turbulent kinetic energy ( $k_t$ ). The horizontal black dashed line indicates the initial bed elevation,  $\delta_b = 0$ . The vertical dashed line indicates the lateral interface of the array ( $y = b$ ). . . . . 158
- 7.6 The laterally averaged net deposition  $\frac{1}{b} \int_0^b \delta_b dy$  at each streamwise position along the array. The dashed horizontal line represents the average value in the fully developed region ( $x > L_i$ ). . . . . 159
- 7.7 The lateral profiles of (a) Reynolds shear stress ( $-\overline{u'v'}$ ) and (b) fluctuating span-wise velocity ( $v_{rms}$ ) for low-density patch with and without a splitter plate at the patch centerline. The dashed lines indicate the lateral interface of the patch,  $y = b$ . 160
- 7.8 Lateral profiles of normalized fluctuating cross-stream velocity ( $v_{rms}/U_o$ ) at  $x = 318$  cm and 328 cm, i.e., 50 cm and 60 cm after the trailing edge of the high flow blockage patch and low flow blockage patch, respectively. The dashed line indicates the half width of the patch,  $y = b$ . . . . . 161
- 7.9 Comparison of flow statistics with initially flat bed ( $t = 0$ , blue circles) and with fully-developed bedforms ( $t = 96$  hr, orange symbols). (a) time-averaged streamwise velocity ( $\bar{u}$ ), (b) Reynolds shear stress ( $-\overline{u'v'}$ ), (c) turbulent kinetic energy ( $k_t$ ). Profiles measured at  $x = 249$  cm in the fully-developed region of the patch ( $x > L_i$ ) for high flow blockage canopy ( $C_{Dab} = 3.88$ ). The vertical dashed line indicates the lateral interface of the array,  $y = b$ . . . . . 162
- 7.10 (a, b, c, d) As bedforms in the wake grew, the vortex street in the wake was weakened, as illustrated by dye visualization. (e, f) PSD in the wake over flat bed ( $t = 0$ ) and over deformed bed ( $t = 96$  hr), measured at  $x = 318$  cm, which was 50 cm downstream of the trailing edge of the patch and close to the peak of the deposition (Figure 7.3a). The horizontal dashed line indicates the dimensionless frequency of a von Karman vortex  $2f_{VK}b/U_2 = 0.2$ . The vertical dashed line indicates the lateral interface of the array. . . . . 164

|      |                                                                                                                                                                                                                                                                                                                   |     |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 7.11 | The lateral distribution of (a) time-averaged streamwise velocity ( $\bar{u}$ ), (b) fluctuating spanwise velocity ( $v_{rms}$ ), (c) turbulent kinetic energy ( $k_t$ ), at $x = 318$ cm, i.e., 50 cm after the trailing edge of the patch. The dashed lines indicate half width of the patch, $y = b$ . . . . . | 165 |
| 7.12 | Ratio of the von Karman vortex street frequency, $f_{VK}$ , in the patch wake to the frequency of the KH vortices along the patch edge, $f_{KH}$ . The solid line indicates $f_{VK} = f_{KH}$ and the dashed lines indicates $\pm 20\%$ deviation. . . . .                                                        | 167 |
| 7.13 | Power spectral density of the lateral velocity ( $S_{vv}$ ) at $(x, y) = (249 \text{ cm}, 20 \text{ cm})$ shows the difference between stem-scale vortex frequency ( $f_d = 0.85 \text{ Hz}$ ) and the Kelvin–Helmholtz vortex frequency ( $f_{KH} = 0.2 \text{ Hz}$ ) . . . . .                                  | 168 |

# List of Tables

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 3.1 | Summary of hydraulic conditions. $U_\infty$ is the mean upstream velocity. $h$ is the water depth. For mobile-bed test, $h$ is the water depth above the top of the initially flat sand layer. $Fr = U_\infty/(gh)^{1/2}$ is the channel Froude number and $Re = U_\infty h/\nu$ is the channel Reynolds number. . . . .                                                                                                                                                                                                                       | 51  |
| 3.2 | Summary of data collection and ADV configuration. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 55  |
| 4.1 | Summary of experimental parameters. $L$ is the length of the patch. $W$ is the width of the patch. $N$ is the number of rods per unit bed area. $a$ is the frontal area per unit volume. $\Phi$ is the average solid volume fraction. $C_{Dab}$ is the patch flow-blockage with $b$ is half width of the patch $b = W/2$ . $L_{i,c}$ is the calculated interior adjustment length according to Equation (3.23). . . . .                                                                                                                        | 71  |
| 4.2 | Measured parameters. VK and KH indicate the presence (Y) or absence (N) of Karman vortex street and Kelvin-Helmholtz vortex street respectively. . . . .                                                                                                                                                                                                                                                                                                                                                                                       | 78  |
| 6.1 | Experimental parameters and measured data. $dx$ and $dy$ is the stem's center-to-center spacing in the streamwise and spanwise directions respectively. $U_1$ is the equilibrium velocity after flow adjustment within the vegetated zone. $U_2$ is the equilibrium velocity after flow adjustment in the main channel. $u_*$ is the friction velocity across the side edge of the patch, defined in Eq. (6.3). Number in the bracket indicates uncertainty. . . . .                                                                           | 111 |
| 7.1 | Summary of experimental parameters. Bracketed numbers indicate uncertainty. $L_i$ is the measured interior adjustment length. $L_{i,c}$ is the calculated interior adjustment length, Eq. 3.23. $L_s$ is the length of the scour region measured from the patch leading edge, and $h_s$ is the depth of the scour. $L_d$ and $h_d$ are the length and height of the depositional dune within the patch. $V_e$ is the volume of erosion at the leading edge of the patch. $V_d$ is the volume of the deposition mound inside the patch. . . . . | 149 |
| 7.2 | The predicted and measured frequencies for Kelvin–Helmholtz vortices ( $f_{KH}$ ) and von Karman vortices ( $f_{VK}$ ). The asterisk (*) indicates the data measured in Chapter 4. Numbers in brackets are uncertainties. . . . .                                                                                                                                                                                                                                                                                                              | 167 |



# Chapter 1

## Introduction

### 1.1 Significance and Values

Aquatic vegetation is a critical component in coastal and riverine ecosystems, forming important wetland and littoral habitat. Aquatic plants provide a wide range of ecosystem services. For instance, the existence of such aquatic vegetation patch may (1) purify water, as aquatic plants can directly absorb pollutants, such as nitrogen, phosphorus, and heavy metals, as well as promote oxidation and decomposition of contaminants and purify the rivers by affecting their micro-environment (Kirzhner et al. 2009, Nagelkerken et al. 2014, Rao et al. 2018, Sonnenwald et al. 2019, Sabokrouhiyeh et al. 2020); (2) increase biodiversity, as aquatic vegetation can provide oxygen, food, as well as create habitats with spatially heterogeneous stream velocities for aquatic organisms (Kemp et al. 2000, Beechie et al. 2006, O'Hare et al. 2007, 2010); (3) enhance bank stability and mitigate the hazards of floods and tsunamis, as aquatic plants can protect riverbanks and coastlines by slowing flow velocity, dissipating wave energy, promoting sediment deposition, and resisting erosion (Tsujiimoto 1999, Lorenz et al. 2015, Nowacki et al. 2017, Fairchild et al. 2021, Li, Chiu & Chen 2025); (4) improve landscaping, as aquatic plant provides recreational activities and improves the physical attractiveness of the surroundings (Arsénio et al. 2020, Riis et al. 2020); (5) carbon storage, as underwater grasses globally can store approximately 10 percent of the carbon in the entire ocean in the form of rich aquatic soils (Fourqurean et al. 2012, Greiner et al. 2013).

Aquatic vegetation alters the mean and turbulent flow field (Pujol et al. 2010, Li et al. 2019), by introducing additional hydraulic resistance (Tanino & Nepf 2008*a*, Etminan et al. 2017), which is greatly dependent on its own features, such as plant morphology (Chembolu et al. 2019), flexibility (Caroppi et al. 2021), spatial arrangement, patch density (Zong & Nepf 2012), and patch size (Chen, Ortiz, Zong & Nepf 2012). Each plant behaves as a physical barrier that obstructs and redirects the flow, creating a spatially heterogeneous velocity distribution around the plant (Tanino & Nepf 2008*b*). Directly upstream and downstream of a stem, the velocity is

mitigated. However, in the region between two stems, the velocity is enhanced. The velocity variation leads to a stem-scale turbulence enhancement. At the blade scale, a boundary layer forms on the plant surface. For a community of plants, vegetation patch or canopy acts as a porous obstruction, creating slow-moving flow within the obstructed region and fast-moving flow outside the patch. The velocity shear across the patch interface triggers the formation of patch-scale turbulence, with implication on mass and momentum exchange between the open region and vegetated area. Additionally, vegetation patches can act as natural buffers against destructive flow events, mitigating flood impacts by reducing peak flow velocities and enhancing sediment retention (Anderson et al. 2006, Métivier et al. 2016). However, excessive vegetation growth can sometimes lead to channel constriction and increase the risk of localized flooding, necessitating a balanced approach to river management (Reid et al. 2013).

Vegetation is particularly noted for retaining sediment and maintaining bed stability in coastal and riverine ecosystems (Orth et al. 2020, Temmink et al. 2022, Xu, Esposito, Beltrán-Burgos & Nepf 2022). Vegetation introduces additional resistance (James et al. 2004, Aberle & Järvelä 2013), which reduces velocity (Liu et al. 2020). This tends to enhance sediment deposition and retention of sediment (Sand-jensen 1998, Bouma et al. 2007, Follett & Nepf 2012), which can promote the growth of ridges and islands (Larsen & Harvey 2010, Gu et al. 2019) and affect the vegetation growth and distribution in rivers by delivering organic materials adhered to sediment particles (Vandenbruwaene et al. 2011). In addition, well-developed root systems create a barrier at the sediment-water interface, increasing the particle adsorption and restraining the sediment resuspension. Besides, vegetation roots can withstand high tensile stresses, thereby enhancing the shear strength of bank materials and reducing the the probability of mass failure (Pollen et al. 2004). However, vegetation also generates turbulence (Tanino & Nepf 2008*b*, Yager & Schmeeckle 2013), facilitating sediment resuspension (Yang et al. 2016, Tinoco & Coco 2016), leading to erosion and reduction of bed elevation (Norris et al. 2021). The presence of root increases infiltration or adds surcharge, reducing bank stability (Simon & Collison 2002).

The establishment of vegetation affects local hydrodynamics and sedimentation, which in turn shapes flow dynamics (Colombini & Stocchino 2005, 2012) and the reproduction and persistence of aquatic plants (Gurnell 2014, Gran et al. 2015). For example, bedform evolution alters the flow structure, which influences the sediment movement (Chang et al. 2017). Fast currents may cause mechanical damages on the vegetation (Wang et al. 2010). Besides, high flow velocities also promote sediment resuspension where vegetation is sparse. The resulting increase in sediment concentration limits light penetration, thereby restricting the growth of vegetation (Biggs 1996, Sousa et al. 2010). However, sediment resuspension releases nutrients from the bed material and the water movements water flow assists in distributing seeds and fragments of aquatic plants. In addition to hydrodynamics, sediment movement is equally



Figure 1.1: Aquatic vegetation in Walden Pond.

important for the persistence of vegetation. The sediment loss destabilizes the root system of the plants, which is unfavorable for the continued growth of the vegetation (Henry et al. 1996, Edmaier et al. 2015, Calvani et al. 2019). The attachment of suspended particles to the surfaces of aquatic plants weakens photosynthesis and impedes the transfer of gases and nutrients between the plant and its aquatic environment. The accumulation of sediments in vegetated patches results in elevated substrates and better light availability, promoting further vegetation colonization (Corenblit et al. 2007, Nardin et al. 2018). However, excessive accumulation of sediments can smother vegetation by limiting oxygen availability (Dosskey et al. 2010). These feedback mechanisms complicate predictions of how vegetation distribution impacts sediment retention and river morphology, and contributes to a more diverse aquatic ecosystem.

According to Costanza et al. (2014), the annual global economic value of submerged aquatic vegetation is estimated to be \$6.8 trillion. On average, coastal wetlands saved \$2.7 million per estuary annually in damage costs (Fairchild et al. 2021), which is substantially higher than the value of other salt marsh services like carbon storage (Beaumont et al. 2014, Lockwood & Drakeford 2021) or livestock grazing (Barbier et al. 2011). Unfortunately, during the past decades, vegetation has been removed or lost from rivers, marines (Waycott et al. 2009), deltas (Nittrouer et al. 2012) and lakes (Zhang et al. 2017), due to natural causes and agricultural and industrial land-use (Coleman et al. 2008, Botrel & Maranger 2023, Elsey-Quirk et al. 2024). For instance, coastal Louisiana has experienced rapid wetland loss over the past century, with approximately 5,000 km<sup>2</sup> disappearing between 1932 and 2016 (Couvillion et al. 2017). 72.4% of 170 investigated lakes experienced a decline in aquatic vegetation from the early 1980s to 2022, encompassing both submerged and overall aquatic vegetation (Hou et al. 2024). In the past 50 to 100 years, seagrass species have suffered a 25% to 50% reduction worldwide, primarily due

to industrial and agricultural land use and dredging activities (Pendleton et al. 2012, Dunic et al. 2021). Given the importance of vegetation in shaping and enhancing aquatic ecosystem, there is a growing interest in restoring and managing these systems (Minderhoud et al. 2019). To inform restoration and management practices, it is crucial to comprehend the interplay between flow, vegetation, and sediment transport (Paola et al. 2011, Fagherazzi et al. 2017).

## 1.2 Objectives

The complicated feedback mechanisms between vegetation growth, flow structure, and sediment movement pose a significant challenge, particularly in predicting long-term morphology evolution. The objectives of this research include:

(1) to evaluate the impact of vegetation density and patch dimensions on interior velocity adjustment and wake structure, and characterize wake von Karman vortex formation with the velocity shear at the end of the vegetation patch (**Chapter 4**);

(2) to predict the initiation of Kelvin-Helmholtz vortices at the trailing edge of the patch and to detect the influence of patch-edge Kelvin-Helmholtz vortices on the wake structure (**Chapter 5**);

(3) to examine the influence of flow confinement on velocity adjustment and shear structure, as well as the shear interaction in a symmetrical vegetation-channel-vegetation system (**Chapter 6**);

(4) to investigate the interaction between the flow structures within and around a rectangular vegetation patch and the development of the bedform, focusing on patch-scale coherent structures (**Chapter 7**).

## 1.3 Outline of the thesis

The whole thesis has eight chapters.

**Chapter 1** gives an introduction, including the significance and values of this research topics, the objectives of this study, and the outlines of this thesis.

**Chapter 2** reviews previous studies on vegetated flows and leading sediment transport and bedform development.

**Chapter 3** presents the research methods, covering the experimental setup, materials, data collection and data treatment.

**Chapter 4** investigates the combined effects of patch density and aspect ratio on wake structure.

**Chapter 5** reveals the influence of the Kelvin-Helmholtz vortices initiated at the side interfaces of the patch on the wake structure.

**Chapter 6** examines the interaction of Kelvin-Helmholtz vortices in a vegetation-channel-vegetation system consisting of an open channel partially covered with symmetrically distributed arrays of cylindrical surface-piercing plants.

**Chapter 7** connects the flow structure and morphological changes within and around a rectangular array of emergent vegetation, revealing the flow-vegetation-morphology interaction.

**Chapter 8** summarizes the findings and limitations of this study, and gives recommendations for future research.

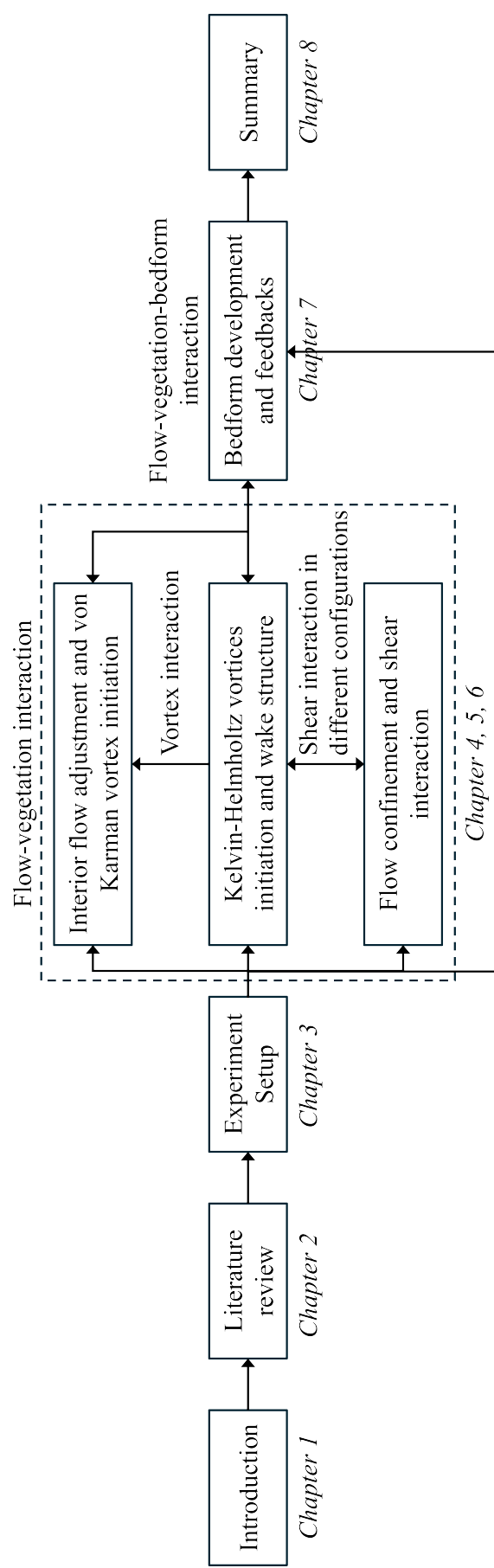


Figure 1.2: The outline of the thesis.

# Chapter 2

## Literature review

To better characterize the hydraulic effect of aquatic vegetation, here we introduce some key parameters that define its characteristics. By defining plant height as  $H$  and water depth as  $h$ , the submergence ratio,  $h/H$ , can be used to classify plants as emergent ( $h/H \leq 1$ ), or submerged ( $h/H > 1$ ). Defining the width of the vegetation patch as  $W$  and channel width as  $B$ ,  $W/B$  indicates whether the patch is finite-width ( $W/B < 1$ ), or channel-spanning ( $W/B = 1$ ). Aquatic plants may be categorized as either rigid or flexible, based on their tendency to undergo bending when exposed to water flow. Emergent vegetation density can be quantified by the solid volume fraction of plant stems, with  $d$  as the mean stem diameter (m) and  $N$  as the number of stems per unit bed area ( $\text{m}^{-2}$ ),

$$\Phi = \frac{N\pi d^2}{4} \quad (2.1)$$

and by front area per volume ( $\text{m}^{-1}$ ),

$$a = Nd \quad (2.2)$$

## 2.1 Interaction between vegetation and water flow

### 2.1.1 Stem-scale structure

Within vegetated areas, flow is diverted around individual stems or blades, resulting in spatial heterogeneity in the velocity field at the scale of the vegetation (Martino et al. 2012, Nepf 2012b, Kalaryti et al. 2025). For the individual element, the stem diameter (or blade width)  $d$  defines the stem Reynolds number,  $Re_d = Ud/\nu$ . When  $Re_d > \approx 100$ , the patch elements will generate stem-scale vortices (Liu & Nepf 2016) and vortex shedding from individual cylinders becomes the primary source of turbulent kinetic energy (Ricardo et al. 2014). The dominant length scale of the turbulence,  $l$ , is determined by the smaller of the stem diameter,  $d$ , or the

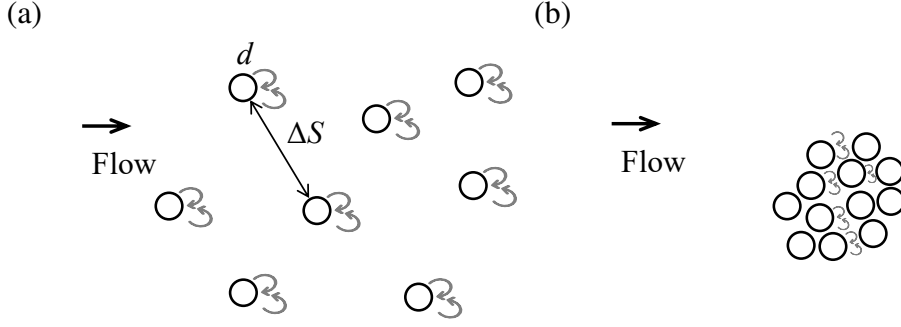


Figure 2.1: Turbulent eddies of characteristic size  $l$  produced in an array of cylinders with uniform stem diameter  $d$  and average distance to the nearest neighboring stem  $\Delta S$ . (a) Sparse array: eddy size is governed by the cylinder diameter, i.e.,  $l \sim d$ . (b) Dense array: eddy size is governed by the cylinder spacing, i.e.,  $l \sim \Delta S$ . This figure is modified from Tanino & Nepf (2008b).

mean distance to the closest adjacent stem,  $\Delta S$  (Tanino & Nepf 2008b). At high stem densities, where  $\Delta S < d$ , turbulence develops within the pore channels, making  $l$  equal to  $\Delta S$ . Conversely, when  $\Delta S \geq d$ , turbulence is generated in the stem wakes, and  $l = d$  (Tanino & Nepf 2008b). Even in very sparse patches (e.g.,  $\Phi = 0.6\%$ ), turbulence production within stem wakes can be comparable to or greater than that generated by bed shear (Nepf et al. 1997, Nepf & Vivoni 2000). Consequently, turbulence levels are governed by the drag induced by the vegetation patch rather than by the bed-friction velocity. Vortex generation in the wakes of stems transfers energy from the mean flow (represented by the mean patch drag) to turbulent kinetic energy ( $k_t$ ). Assuming a 100% efficient conversion, the rate of turbulent energy production is equal to the rate at which the flow performs work against the patch drag. Thus, the stem-scale  $k_t$  within the patch can be estimated as (Tanino & Nepf 2008b)

$$\frac{\sqrt{\langle k_t \rangle}}{\langle \bar{u} \rangle} \approx \left( C_D \frac{l}{d} \frac{2\Phi}{(1-\Phi)\pi} \right)^{1/3}. \quad (2.3)$$

Here,  $l = \min(d, \Delta S)$ ,  $C_D$  is the drag coefficient of the array elements and  $\langle \bar{u} \rangle$  is the local temporally- and spatially-averaged velocity. Notably, only form drag is transformed into turbulent kinetic energy, whereas viscous drag is dissipated directly in the form of heat. For rigid plants, drag is dominated by form drag, making Equation (2.3) a reasonable approximation. However, for flexible vegetation, viscous drag becomes significant, and Equation (2.3) overestimate stem-scale turbulence production. The contributions of viscous and form drag vary with plant morphology and alignment of the blades and stems, with streamlined (aligned) elements favoring viscous drag and bluff (unaligned) elements favoring form drag.



Nepf (1999) reported that increasing vegetation density has competing effects on turbulent kinetic energy. As vegetation density increases, hydraulic resistance mitigates the in-patch velocity compared to that over a bare bed, with in-patch velocity decreasing monotonically as density increases. Conversely, greater vegetation density also promotes turbulence generation in the wakes of stems. Overall, turbulent kinetic energy initially increases with vegetation density, but after reaching a peak, it declines as plant density increases further.

Matsumoto et al. (2025) investigated the effects of flexible vegetation element deflection by comparing the flow fields around a single inclined element and an upright one. They observed that, on the sides of the single inclined vegetation element, downward flows are induced by local pressure gradient along the vegetation element surface. Subsequently, upward flows develop, transporting high-momentum fluid into the region behind the inclined element. Consequently, the deflection of the plant develops a rotating secondary flow, which facilitates transverse sediment transport across the side interfaces of the patch and enhances sediment deposition in the wake region. In addition to the deflection of the element, the dynamic movement of the element may influence the flow structure (Albayrak et al. 2013). What's more, Albayrak et al. (2011) investigated flow–plant interactions at the leaf scale, focusing on how leaf shape, serration, surface roughness, and flexural rigidity influence drag force. Their results showed that leaf shape is the primary factor governing flow–leaf interactions, while flexural rigidity, serration, and surface roughness further modulate the magnitude of this effect.

## 2.1.2 Flow adjustment and distribution

When flow approaches a vegetation patch, it redistributes both within and around the patch (Figure 2.2). First, the fluid decelerates upstream of the patch due to an increase in pressure, which creates a pressure gradient that diverts flow laterally. This region is called the upstream adjustment region (Rominger & Nepf 2011). Second, after entering the patch, the velocity continues to decrease, due to the vegetation-induced drag resistance (Wang et al. 2019, Rominger & Nepf 2011). This streamwise deceleration is accompanied by a flow diversion toward the patch edges, which is defined as interior adjustment region. The flow deflection, both upstream and within the patch, intensifies with increasing vegetation density (Okamoto & Nezu 2013), leading to a lower velocity in the vegetated region and a higher velocity in the adjacent free stream (Peng et al. 2024). Based on scaling analysis and laboratory experiments, Rominger & Nepf (2011) proposed that, for an emergent rectangular vegetation patch, the length of the interior adjustment region ( $L_i$ ) depends on the patch flow-blockage, described by  $C_{Dab}$ , in which  $b$  is the half width of the patch,  $C_D$  is the drag coefficient,  $a$  is the front area per volume. For high flow-blockage patches ( $C_{Dab} \geq 2$ ),  $L_i \sim b$ . For low flow-blockage patch ( $C_{Dab} < 2$ ),  $L_i$  is

dominated by the patch drag length scale,  $(C_{Da})^{-1}$ ,

$$L_i = \begin{cases} (3.0 \pm 0.3) \left[ \frac{2}{C_{Da}} (1 + (C_{Dab})^2) \right], & C_{Dab} < 2 \\ (7.0 \pm 0.4)b, & C_{Dab} \geq 2. \end{cases} \quad (2.4)$$

Third, beyond the adjustment region, shear layers and their associated vortices form and develop along the flow-parallel edges, extending into both the vegetation patch and the adjacent open areas. For high flow-blockage patches ( $C_{Dab} \geq 2$ ), the penetration of shear-layer vortices is less than half width of the patch ( $\delta_l < b$ ), so that the interior flow is determined by a balance between the pressure gradient and the drag imposed by the vegetation, leading to a constant interior velocity,

$$\frac{\langle \bar{u} \rangle}{U_\infty} = \sqrt{\frac{C_f}{h} \frac{(1 - \Phi)}{C_{Da}}}, \quad (2.5)$$

in which  $C_f$  is the bed friction coefficient,  $h$  is the water depth and  $U_\infty$  is the far upstream velocity which is not affected by the vegetation patch. Conversely, for low flow-blockage patches ( $C_{Dab} < 2$ ), shear-layer vortices penetrate more than half the width of the patch ( $\delta_l \geq b$ ), the interior flow is controlled by a balance between the turbulent stress gradient and canopy drag

$$\frac{\langle \bar{u} \rangle}{U_\infty} = \frac{1}{U_\infty} \sqrt{\frac{u_*^2}{b} \frac{2(1 - \Phi)}{C_{Da}}}, \quad (2.6)$$

where,

$$u_* = \sqrt{-\langle u'v' \rangle_{y=b}}. \quad (2.7)$$

The vortex interaction across the patch width results in a velocity recovery before the end of the patch (Rominger & Nepf 2011). Moreover, to predict the evolution of streamwise velocity within and around an emergent patch of model vegetation, Liu & Shan (2019) developed an analytical model and Liu et al. (2020) proposed a model based on exponential decay, but they only considered the scenario where the shear-layer vortices did not penetrate to the patch centerline ( $\delta_l < b$ ).

Similar flow adjustment was observed in submerged vegetation patches (Tang et al. 2020), along with vertical flow diversion. Chen et al. (2013) developed a two-layer model to predict the interior adjustment length ( $L_i$ ) of a channel-spanning submerged patch of rigid circular cylinders

$$\frac{L_i}{H} = (6.9 \pm 1.1)(1 - \Phi) + \frac{3.0 \pm 0.4}{C_{Da}H}(1 - \Phi), \quad (2.8)$$

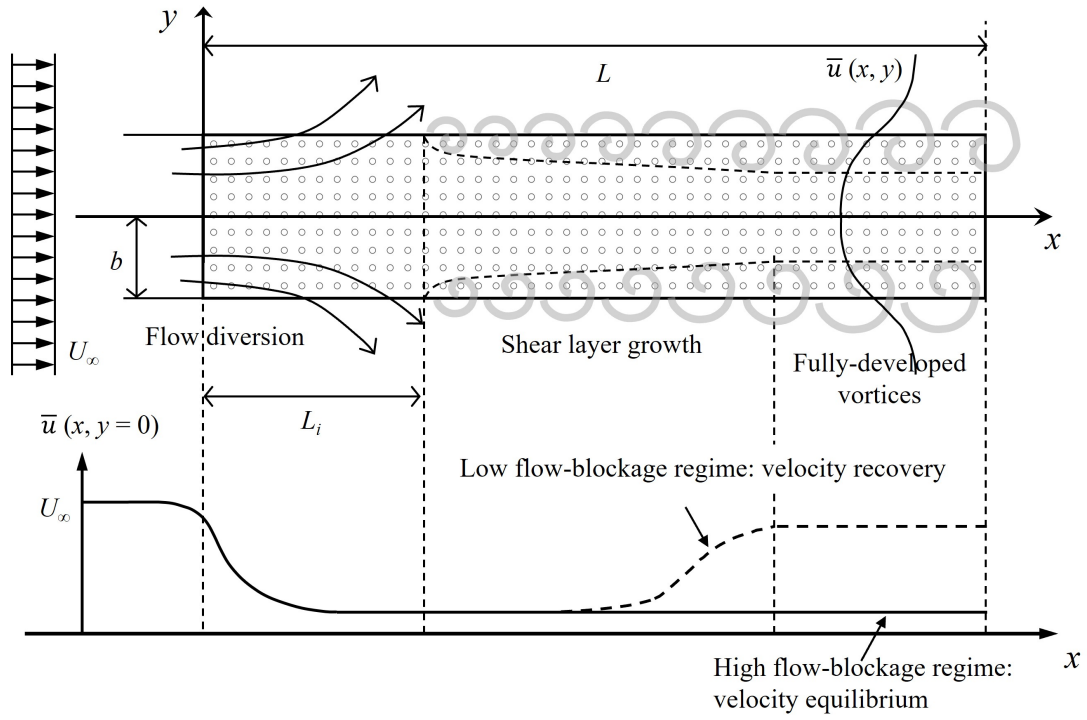


Figure 2.2: Conceptual diagram for flow adjustment for an instream emergent vegetation patch the corresponding streamwise velocity adjustment along the patch centerline. This figure is adapted from Rominger & Nepf (2011).  $L_i$  is the interior adjustment length. Low-flow blockage regime corresponds to  $C_D ab < 2$  and high-flow blockage regime corresponds to  $C_D ab \geq 2$ .

and the streamwise velocity within the patch in the fully developed region ( $U_1$ ),

$$\frac{U_1}{U_\infty} = \frac{1}{1 - \frac{H}{h}\Phi + \sqrt{\frac{C_{Da}H}{2C(1-\Phi)} \left(\frac{h-H}{h}\right)^3}}, \quad (2.9)$$

in which  $H$  is height of the submerged patch,  $C$  is the coefficient describing momentum exchange between the upper overlying and lower vegetated regions. Based on the roughness scaling, previous studies (Gioia & Bombardelli 2001, Konings et al. 2012) have suggested that

$$C = K_c \left( \frac{\delta_e}{h} \right) \quad (2.10)$$

where  $\delta_e$  is the vertical penetration thickness and  $K_c$  is an empirical factor, with  $K_c = 0.07 \pm 0.02$  for rigid canopies (Chen et al. 2013). The penetration length varies inversely with canopy drag,  $\delta_e \sim (C_{Da})^{-1}$  (Nepf et al. 2007), with a scaling constant of  $0.3 \pm 0.1$  for  $10^{-3} < (C_{Da})^{-1} < 10^2$  (Ghisalberti & Nepf 2009). Additionally, both water depth and canopy height may impose constraints on the penetration length (Nepf & Vivoni 2000, Konings et al. 2012), leading to

$$\delta_e = \min \left( \frac{0.3 \pm 0.1}{C_{Da}}, h - H, H \right). \quad (2.11)$$

However, Rominger & Nepf (2011) and Chen et al. (2013) considered emergent patches of finite width and submerged patches that span the channel width, both of which were treated as two-dimensional. Furthermore, to investigate velocity adjustment in a three-dimensional submerged patch of finite width, Lei & Nepf (2021) developed an analytical model and showed that reducing the canopy width from 100% to 12.8% of the channel width resulted in faster velocity adjustment at the leading edge and a lower fully developed interior velocity. For flexible submerged patches, Tang et al. (2020) demonstrated that interior flow adjustment varied linearly with the deflected height of the vegetation.

In contrast to submerged canopies that impede flow near the channel bed, floating vegetation canopies obstruct flow near the water surface, yet both generate similar flow structures (Li et al. 2020). For instance, the flow adjustment near a floating vegetation canopy can also be divided into four regions (Yu, Jiang, Shi, Zhou, Liu & Zhang 2019): the incoming flow adjustment region, the initial adjustment region, the shear layer developing region, and the fully developed region. The vertical velocity profile changes along the streamwise direction (Zhao et al. 2017), from a ‘J’ shape in the incoming flow adjustment region to an ‘S’ shape in the developing and fully developed regions. Gui et al. (2023) also developed a model to predict the length of flow adjustment,

$$\frac{L_i}{H} = 2.8 + 3.4 \frac{1}{C_{Da}H} + 3.7 \left( \frac{h-H}{h} \right), \quad (2.12)$$

The evolution of the shear layer in floating vegetation canopies is limited by the canopy height,  $H$ , and the height of the free-flow region below the canopy,  $h - H$ , (Gui, Shan & Liu 2024)

$$\delta_e = \min \left( \frac{0.13 \pm 0.02}{C_{Da}}, h - H, H \right), \quad (2.13)$$

which is similar to Eq. 2.11. The floating vegetation canopies significantly increase the flow resistance at the water surface, resulting in a hyperbolic-type velocity distribution in the region between the vegetation and bed, similar to the flow in ice-covered channels. Similarly, Tang, Singh & Rahimi (2025) introduced a semi-analytical model, utilizing parameters such as blockage ratio, canopy density and drag, and bed friction, to estimate the vertical distribution of streamwise velocities in open channel flows with floating rigid vegetation.

Furthermore, in addition to plant density and patch dimensions, the spatial arrangement of elements within a vegetation array can also influence velocity adjustment (Zhao et al. 2015, Park & Hwang 2019, Shan et al. 2019, Nair et al. 2023). Liu, Huai, Tang, Wang & Yuan (2024) demonstrated that, given the same density, aligned stem arrangements in vegetation patches led to less lateral flow deflection than staggered arrangements as hydraulic resistance was substantially higher for staggered than aligned configurations (Savio et al. 2023). He, An, Ghisalberti, Draper, Ren, Branson & Cheng (2024) attributed the effects of element arrangement on velocity adjustment to the interaction between wakes of individual elements. Specially, for an in-line arrangement, downstream plants are situated directly within the wake of those upstream, which leads to decreased velocity and drag, with the greatest force observed at the leading edge of patch (Maza et al. 2017). Furthermore, a uniform spacing between vegetation elements creates preferential flow paths within the array, which produces local high velocity and strong turbulence (Chang & Constantinescu 2015, Koken & Constantinescu 2021). Ricardo et al. (2016) conducted laboratory experiments to investigate the effects of spatial non-uniformity of vegetation arrays by varying the longitudinal vegetation density. The results revealed that the time-averaged mean flow field is greatly impacted by locally varying vegetation density, which serves as a spatial memory of the upstream stem distribution.

To evaluate the velocity redistribution between the high-discharge open region and the low-discharge vegetation region, numerous models have been developed to characterize the velocity profile across the vegetation interface. For instance, Yan, Shan, Liu & Liu (2022) proposed an analytical model to predict the lateral profile of velocity in partially vegetated channels, verified by twenty sets of experimental data covering a wide range of vegetation and flow conditions. For a submerged rigid vegetation patch, Liu et al. (2008) and Yang & Choi (2010) observed that velocity within the vegetation array remains uniform with depth, while above the vegetation, the velocity profile follows a logarithmic distribution, with inflection points marking the boundaries. To account for the interaction between water flow and morphological response of

submerged flexible vegetation, Wang, Zhao, Ren, Liu, Dong, Li, Fan & Wu (2023) introduced a new power law for vertical velocity distribution, incorporating the concept of a vegetated riverbed and assuming a linear relationship between vegetation drag and velocity. Furthermore, for submerged flexible vegetation patches, Li et al. (2014) identified three distinct vertical layers in the velocity distribution: the upper non-vegetated layer, the middle canopy layer, and the lower sheath layer. In the upper non-vegetated layer, velocity profiles followed the logarithmic law, and an empirical equation was developed based on observed data. As vegetation density increases, velocity and flow rate increase in the upper non-vegetated layer, but decrease in the middle canopy and lower sheath layers. The results also showed that, with higher vegetation density, the ratio of average flow discharge between the non-vegetated and vegetated layers increases exponentially. Moreover, to consider the influence of plant morphology on velocity adjustment, Shan et al. (2023) predicted the vertical velocity distribution using the estimated depth-averaged velocity and the frontal area of the plants. Meng et al. (2025) introduced a contraction coefficient to measure the decrease in the frontal projected area of flexible plants under flow. With increasing bulk velocity, this coefficient rises and then stabilizes due to the reduction in frontal area. These findings highlight the importance of accounting for vegetation deformation, specifically changes in frontal area, when predicting flow velocity, particularly under high-velocity river conditions.

### 2.1.3 Flow structure in submerged vegetation patch

The flow behavior within and around a submerged vegetation patch is governed by the relative contributions of bed drag and patch drag (Nepf & Vivoni 2000). When patch drag is less significant than bed drag, the velocity profile resembles that of a turbulent boundary layer (Poggi et al. 2004), with the vegetation contributing to the bed roughness. which is defined as the sparse patch limit (Figure 2.3a). In the sparse patch limit, increasing stem density leads to greater turbulence near the bed. Conversely, in the dense patch limit (Figure 2.3b, 2.3c), patch drag dominates over bed drag, and the discontinuity in drag at the top of the patch generates a shear structure resembling a free shear layer, characterized by an inflection point in the velocity profile near the patch top (Luhar et al. 2008, Monti et al. 2020, Tang, Jia, Zhang, Yi & Dey 2025, Kalaryti et al. 2025). Based on scaling analysis, Belcher et al. (2003) proposed that the threshold distinguishing sparse and dense limits occurs at  $aH = 0.1$ . Velocity measurements by Nepf et al. (2007) further showed that for  $C_D aH < 0.04$ , the velocity follows a rough boundary-layer profile, while for  $C_D aH > 0.1$ , a pronounced inflection point is present. Since the assumption of  $C_D \approx 1$  is often reasonable (Liu & Shan 2019), the measured and theoretical limits are in good agreement.

For turbulent shear layer, the patch-scale vortices attain a characteristic size and a fixed penetration depth into the patch ( $\delta_e$ , Ghisalberti & Nepf (2002, 2009) within approximately

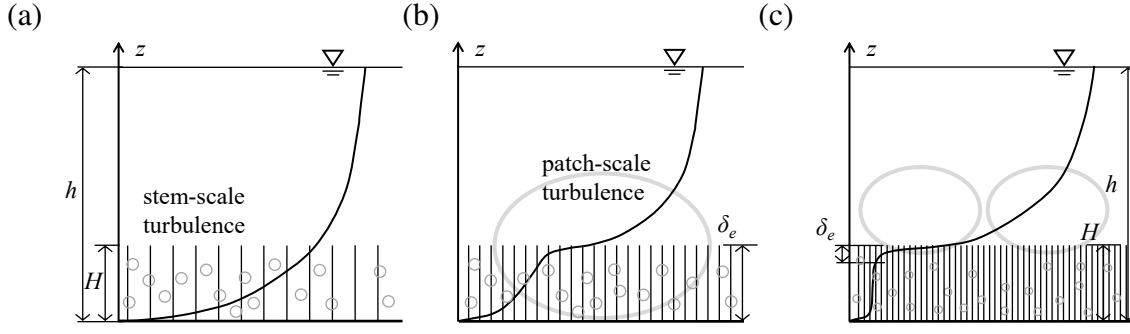


Figure 2.3: The flow structure and vertical distribution of streamwise velocity for submerged vegetation patch.  $H$  is the patch height. (a) For sparse regime ( $aH < 0.1$ ), the velocity follows a rough boundary-layer profile. (b) For intermediate regime ( $0.1 \leq aH < 0.23$ ), shear structure at the top of the patch induces patch-scale turbulence, which penetrates a distance of  $\delta_e$  into the patch. (c) For dense regime ( $aH > 0.23$ ),  $\delta_e < H$ , the bed remains insulated from patch-scale turbulence and is dominated by stem-scale turbulence. This figure is adapted from Nepf (2012a).

$10H$  from the leading edge of the patch. When the shear production that generates patch-scale vortices is balanced by dissipation due to patch drag, the shear layer and its associated vortices cease to grow (Ghisalberti & Nepf 2004). This balance predicts,

$$\delta_e = \frac{0.23 \pm 0.6}{C_{Da}}, \quad (2.14)$$

which has been verified with laboratory experiments (Nepf et al. 2007). Note that Equation. (2.14) is only valid when patches generate a shear layer (i.e.  $C_{Da}H \geq 0.1$ ). For intermediate regime ( $C_{Da}H = 0.1 \sim 0.23$ ), the patch-scale turbulence penetrates to the bed,  $\delta_e = H$ , creating significant turbulence over the entire patch height (Figure 2.3b). For dense regime ( $C_{Da}H > 0.23$ ), the patch-scale turbulence fails to penetrate to the bed,  $\delta_e < H$ . However, Equation. (2.14) for  $\delta_e$  becomes invalid when the submergence ratio  $H/h < 2$ , since interactions with the water surface reduce both the strength and size of patch-scale vortices (Nepf & Vivoni 2000, Wilson et al. 2003, Choi & Kang 2016). Assuming that  $\delta_e$  decreases linearly to zero at  $H/h = 1$ , which is the emergent condition,  $\delta_e$  is estimated to be (Chen et al. 2013),

$$\delta_e = \frac{0.23 \pm 0.6}{C_{Da}} \left( \frac{h}{H} - 1 \right). \quad (2.15)$$

Patches for which  $\delta_e < H$  protect the bed from strong shear-layer turbulence. The region below the shear layer ( $z < H - \delta_e$ ) is dominated by the stem-scale turbulence (Figure 2.3c).

Within the shear layer, the inflection point near the top interface of the patch triggered the formation of coherent structures through Kelvin–Helmholtz (KH) instability (Raupach et al.

1996, Ghisalberti & Nepf 2002, 2004, Caroppi et al. 2019). The frequency of the KH instability is consistent with the natural frequency predicted by linear stability theory for mixing layers (Ho & Huerre 1984),

$$f_{KH} = \frac{0.032\bar{U}}{\theta} \quad (2.16)$$

in which  $\bar{U} = 1/2(U_1 + U_2)$  and

$$\theta = \int_0^h \left[ \frac{1}{4} - \left( \frac{\bar{u}(z) - \bar{U}}{\Delta U} \right)^2 \right] dz. \quad (2.17)$$

$\Delta U = U_2 - U_1$  with  $U_1$  and  $U_2$  being the slow- and fast-moving velocities, respectively,  $\bar{u}(z)$  is the time-averaged streamwise velocity at position  $z$ . In other words, the normalized frequency of KH instability is  $f_{KH}\theta/\bar{U} = 0.032$ . These vortices, referred to as patch-scale turbulence, are distinct from the large-scale boundary-layer turbulence that can develop above deeply submerged or unconfined patches (Belcher et al. 2012), as well as from the small-scale stem-induced turbulence (Tanino & Nepf 2008b). For a deeply submerged patch ( $h/H > 10$ ), patch-scale vortices interact with boundary-layer turbulence, making them highly three-dimensional and increasing secondary instabilities through vortex stretching (Finnigan et al. 2009). In contrast, for shallowly submerged patches ( $h/H \leq 5$ ), commonly observed in aquatic environments, the absence of large-scale boundary-layer turbulence means that patch-scale vortices govern the turbulent dynamics both within and above the patch (Ghisalberti & Nepf 2005, 2009).

Mandel et al. (2019) observed a normalized shedding frequency at the water surface of  $f_{KH}\theta/\bar{U} = 0.064$ , which is twice the theoretical value of the most unstable mode,  $f_{KH}\theta/\bar{U} = 0.032$  (Ho & Huerre 1984). This finding reveals that vortices may evolve between their generation at the patch top interface and their appearance at the free surface. What's more, for submergence ratios ( $h/H$ ) ranging from 1.6 to 3.1, the vortex size was found to be proportional to the open water height rather than the patch height, because of the the flow confinement caused by the water surface.

The formation of shear-layer vortices creates a pronounced flow oscillation, leading to the progressive, coherent waving of the flexible aquatic plants, which is known as the monami (Zampogna et al. 2016, Wong et al. 2020, Okamoto & Nezu 2009, Tschisgale et al. 2021, Wang, He, Dey & Fang 2022a). The frequency of the monami matches that of the KH instability, indicating that monami is a forced response to the instability of the mixing layer (Ghisalberti & Nepf 2002). Specially, the amplitude and frequency of the coherent waving motion are greatly linked to plant properties (Patil & Singh 2010) and flow conditions. For instance, in the case of highly flexible vegetation, the numerical model developed by Wang, He, Dey & Fang (2022a) demonstrated that increasing flow velocity led to a decrease in the wavelength of the coherent waving motion, while both its frequency and amplitude increased. Moreover, an increase in



relative vegetation density results in a greater amplitude of the coherent waving motion, without influencing its wavelength or frequency. Relative to rigid vegetation, the oscillation in flexible vegetation reduces patch drag (Li et al. 2018, Wang, He, Huang, Dey & Fang 2024) and makes additional contributions to intensifying the turbulence intensity near the patch (Wang, He, Dey & Fang 2022b, Wang, He, Huang, Dey & Fang 2023), enhancing turbulent vertical transport of momentum and turbulence stresses penetration of the plant height into the patch (Yang & Choi 2009, Xu, Liu, Wu & Ji 2022, Fu et al. 2023). Moreover, Chen et al. (2011) the vortices formed above a static canopy rotate more rapidly than those above a waving canopy.

The degree of reconfiguration of the vegetation elements strongly depends on two dimensionless parameters, namely vegetation density and Cauchy number (Kim et al. 2024). Cauchy number,  $Ca$ , measures hydrodynamic drag forces relative to restoring elastic forces in flexible structures, with higher values indicating a greater degree of reconfiguration, which is defined as

$$Ca = \frac{(\rho_f/2)U^2WL^3}{E_s I}, \quad (2.18)$$

in which  $\rho_f$  is the fluid density,  $U$  is the bulk velocity,  $W$  is the plant width,  $L$  is the plant height and  $E_s I$  is the flexural rigidity of an individual vegetation element with  $E_s$  being the Young's modulus and  $I$  the second moment of area. As  $Ca$  increases, distinct fluid–structure interaction regimes emerge, as shown in Figure 2.4. For  $Ca \ll 1$ , elastic forces dominate and vegetation elements remain upright (Luhar et al. 2010, Luhar & Nepf 2011). In this regime, a mixing layer forms at the top interface of the vegetation patch (Figure 2.4a), where coherent structures are initiated and convected in flow direction. In the case of intermediate  $Ca$ , elements begin to sway independently with small amplitudes, which is referred to as ‘gently swaying’ (Figure 2.4b). As  $Ca$  increases further, elements undergo greater reconfiguration and present highly coherent waving motions, which is known as monami (Ackerman & Okubo 1993), depicted in Figure 2.4c. At very high  $Ca$ , substantial reconfiguration occurs, with elements predominantly aligning in the flow direction (Figure 2.4d). This alignment suppresses the mixing layer and the associated KH vortices, thereby reducing vertical momentum exchange as the patch top becomes fully covered by reconfigured elements. He et al. (2022) observed that, in highly flexible canopies, stem fluctuations become so minimal that the canopy effectively acts like a rigid structure. They termed this phenomenon ‘high flexibility-induced rigidity’.

#### 2.1.4 Flow through and around patch of finite width

In natural channels, plants frequently occur along the riverbanks. The fringing vegetation patch with a width smaller than that of the channel partially obstructs the cross-section creating a drag differential between the vegetated area and the adjacent free stream region. This drag difference significantly modifies both the mean and turbulent flow structures (Koken & Constantinescu

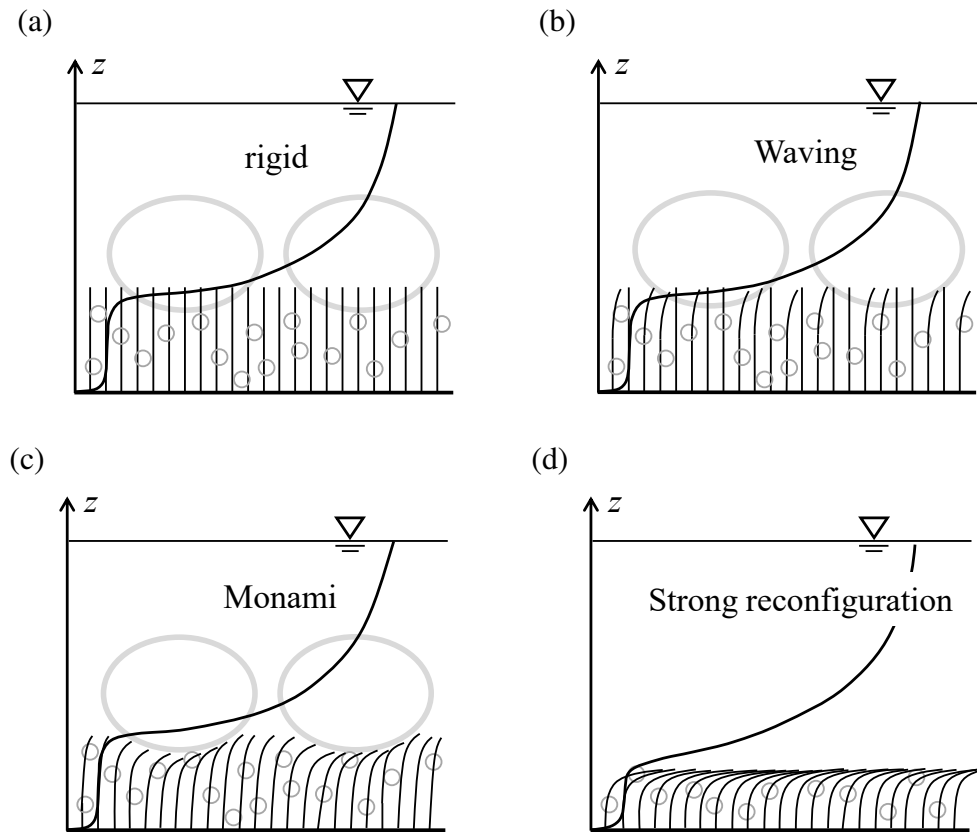


Figure 2.4: Vegetation behaviors with increasing Cauchy number  $Ca$ . Strongly reconfigured vegetation behaves as a rigid body, thereby suppressing the formation of Kelvin–Helmholtz vortices (d). This figure is adapted from Okamoto et al. (2016).

2021, Tang et al. 2023, Wang, Zhang, Jiang, Yao & Yan 2024). Similar to the vertical shear layer generated along the vertical interface of the submerged patches, the horizontal shear layer along the lateral edge may trigger the formation of patch-scale coherent structures when the dimensionless velocity shear

$$\lambda = \frac{U_2 - U_1}{U_2 + U_1} \quad (2.19)$$

is over 0.3 (Caroppi et al. 2019). This critical value was initially observed in shear layers developed in compound channels (Dupuis et al. 2017, Proust et al. 2017). Furthermore,  $\lambda$  can measure the turbulence energy associated with Kelvin–Helmholtz instabilities ( $\propto (U_2 - U_1)^2$ ) relative to the energy associated with bed-friction depth-scale turbulence ( $\propto (0.5(U_2 + U_1))^2$ ) (Proust & Nikora 2020).

Just as a vertical shear layer forms along the top interface of submerged patches, the horizontal shear layer along the lateral edge penetrate into the patch over length  $\delta_I$  and evolve into the open channel over length  $\delta_O$  (Figure 2.5a). Referring to vertical patch-shear layers,  $\delta_I \sim (C_{Da})^{-1}$ . However, the horizontal shear layers ( $\delta_I$ ) exhibit a scale factor that is double that of the vertical shear layers above submerged patches ( $\delta_e$ , Equation 2.14). According to White & Nepf (2007, 2008),

$$\delta_I = \frac{0.5 \pm 0.1}{C_{Da}} \quad (2.20)$$

and

$$\delta_O \sim h/C_f, \quad (2.21)$$

where  $C_f$  is the bed friction coefficient. No apparent correlation is identified between  $\delta_I$  and  $\delta_O$ . For scenarios with significant patch drag ( $C_{Da}$ ), where the shear layer cannot penetrate over the first row of cylinders, the cylinder diameter defines a lower bound for  $\delta_I$ . White & Nepf (2008) suggested that  $\delta_I \approx 1.8d$  in this high-density scenario and developed an empirical expression for the inner penetration thickness,

$$\delta_I = \max \left( \frac{0.5 \pm 0.1}{C_{Da}}, 1.8d \right). \quad (2.22)$$

This relationship was developed from rigid vegetation. However, compared to rigid plants, Caroppi et al. (2021) observed that the dynamic motion of flexible foliated plants leads to deeper inner penetration.

Compared to one-sided along-bank vegetation patches, long emergent patches may also appear within the channel, forming two streamwise lateral interfaces, which allows shear layers to develop at two side edges of the patch (Figure 2.5b). To recognize the geometric similarity with bank vegetation,  $b$  is defined as the half width of the in-flow vegetation patch. If  $b > \delta_I$  ( $C_{Dab} > 0.5$ , according to Equation. 2.22), patch-scale turbulence does not penetrate to the centerline of the patch. In this regime, the interior region beyond the shear layer the interior

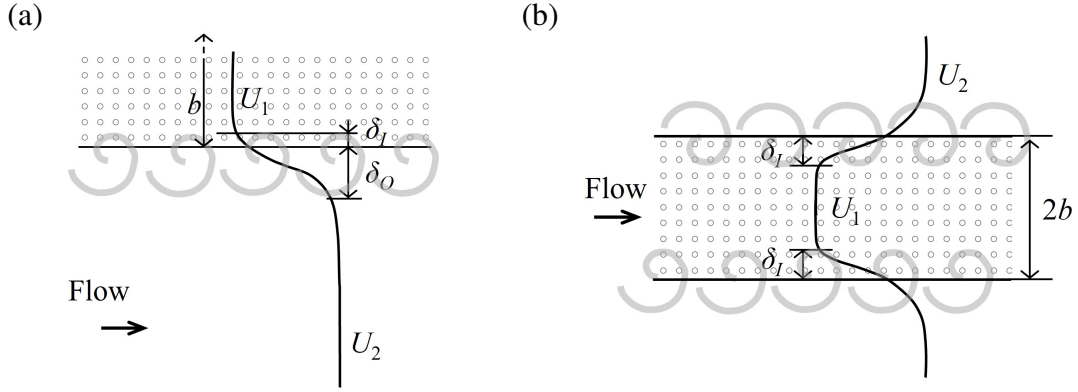


Figure 2.5: The horizontal shear structure formed at the lateral interface(s) of (a) along-bank and (b) in-channel emergent vegetation patch.  $b$  is the width for the along-bank patch, but the half width for the in-channel patch.  $U_1$  and  $U_2$  are the lowest velocity within the vegetation patch and highest velocity adjacent to the patch, respectively.  $\delta_l$  is the penetration of the shear layer into the patch and  $\delta_0$  is the thickness of the shear layer in the bare channel.

region beyond the shear layer ( $-b + \delta_l < y < b - \delta_l$ , where  $y = 0$  denotes the patch centerline) is dominated by stem-scale turbulence. Conversely, when  $C_{Dab} < 0.5$ , is able to reach the centerline, dominating the entire vegetated region. In this regime, the vortices from both sides interact across the patch width, thereby enhancing the turbulence level inside the patch and leading to velocity reacceleration (Rominger & Nepf 2011).

The vortex core is a low-pressure region. If the shear-layer vortices present, their passage along the streamwise interface induces a wave response beyond the shear penetration,  $\delta_l$  (White & Nepf 2007, 2008, Zong & Nepf 2011, Koken & Constantinescu 2021). In the case of in-stream patches, a phase shift between the vortex streets forming on both sides of the patch (Figure 2.5b) creates a cross-patch pressure gradient, which induces a cross-stream velocity inside the patch. This process greatly improves the vortex strength and the momentum exchange between the open region and vegetated zone (Rominger & Nepf 2011). Furthermore, the lateral transport distance associated with this wave response was estimated by the wave orbital radius of the oscillating lateral velocity (Luhar & Nepf 2016),

$$A_w = \sqrt{2}v_{rms}/2\pi f, \quad (2.23)$$

in which  $v_{rms}$  is the fluctuating lateral velocity at the side interface of the patch,  $f$  is the frequency of the shear-layer vortices, as the frequency of the wave response is fixed by the frequency of vortex passage (Zong & Nepf 2011).

Huai et al. (2019) examined the contributions of the coherent structures to the lateral momentum exchange between the vegetated area and open region, using quadrant analysis. Their results showed that, near the interface, sweeps and ejections were the primary contributors to

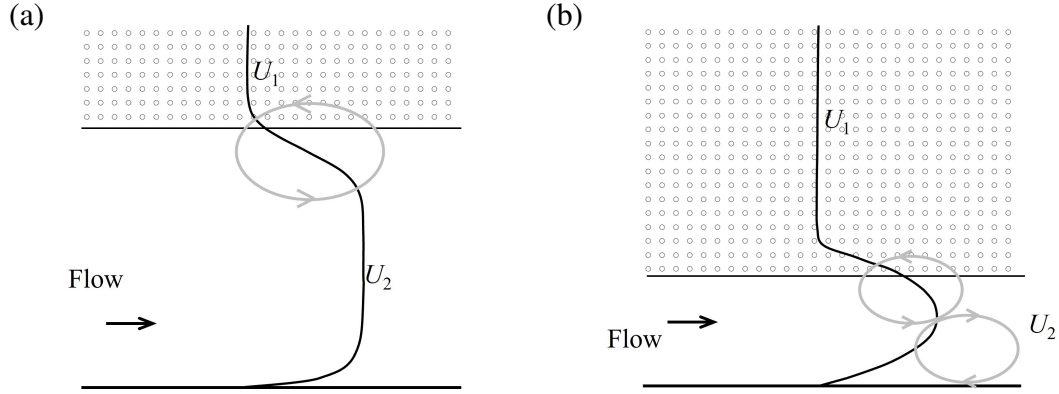


Figure 2.6: The flow structure of (a) sole along-patch vortices at the lateral interface of the array in unconfined conditions; (b) alternating along-patch and along-wall vortices in confined conditions.

Reynolds stress. In contrast, inward and outward interactions dominated further inside the vegetated area. Within the vegetation, sweep events were more contributing than ejections, while outside the vegetated region, ejections became more prominent. Similarly, quadrant analysis of vertical turbulent coherent structures in submerged rigid patches revealed consistent characteristics (Malothu et al. 2025), with sweep events dominating the flow in the slow-moving vegetated layer, and the ejection events prevailing in the fast-moving open-flow layer.

Jia et al. (2022) evaluated the patch blocking effect on the vortex dynamics in a partially vegetated channel using a numerical model. In unconfined conditions, vortices were observed only at the lateral interface of the patch (Figure 2.6a). However, as the blockage ratio (the ratio of the patch width to the channel width) increased, the along-patch vortices could initiate the formation of along-wall vortices, forming a pattern of hybrid along-patch and along-wall paired vortices (Figure 2.6b). In this scenario, the paired vortices propagated in an alternating pattern. Additionally, the size of the along-patch vortices decreased when along-wall vortices presented, characterized by a pronounced decrease in wavelength and an increase in wave number. Lateral velocity profiles typical of shear layer flows, which are hyperbolic tangent with sole along-patch vortices, shifted to parabolic profiles as the hybrid paired vortices became dominant. Furthermore, the interaction of the along-patch vortices and along-wall paired vortices enhanced the shear stress at the lateral interface of the patch, improving the momentum exchange across the side edge.

When the along-bank vegetation patch becomes submerged, vertical and horizontal shear layers originate from the top and lateral interfaces of the patch (Yan et al. 2016, Unigarro Vil-lota et al. 2023, Song, Wang, Duan, Stocchino & Yan 2024). In this configuration, even though the streamwise velocity inside the vegetation patch reached an equilibrium state at the downstream part of the array, secondary flows were detected near the top interface and side interface

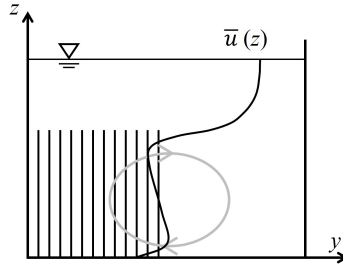


Figure 2.7: The formation of secondary flow near lateral interface of a submerged array partially obstructed the channel, leading to S-shaped vertical velocity profile of streamwise velocity near the lateral interface.

of the patch (Nezu & Onitsuka 2001). This secondary flows was commonly observed in flows over heterogeneous beds, such as those with topographical (Medjnoun et al. 2020) or roughness variations (Anderson et al. 2015). The formation of secondary flows was attributed to the anisotropy in turbulence (Han et al. 2016, Stroh et al. 2020). For a submerged along-bank canopy, Koken & Constantinescu (2023) observed that the flow entered the vegetated region from its top interface and left the patch from its side interface, forming streamwise-oriented secondary flow cells. However, Shi et al. (2023) observed a reverse-rotating secondary circulation, which carries water parcels from vegetated region with low streamwise velocity into open region near the top interface, while carries water parcels from open region with high streamwise velocity into vegetation zone near the side interface. Song, Wang, Duan, Stocchino & Yan (2024) found that the characteristics of cross-sectional secondary flows, such as scale, location, and evolution, varied as the patch expanded laterally. Furthermore, the width-to-depth ratio of the river influenced the direction of secondary circulation above the channel-spanning patches. The streamwise-oriented secondary flow cells moved closer to the lateral interface of the array with increasing submergence ratio (Koken & Constantinescu 2023). The intensity of the secondary flows was influenced by patch density (Choi & Kang 2006). In addition to the secondary flows, higher patch density initiates extra rotating cells located both above and adjacent to the patch (Unigarro Villota et al. 2023), significantly contributing to interfacial momentum exchange (Yan, Duan, Wai, Li & Wang 2022). Moreover, the presence of secondary flows produced a S-shaped velocity profile at the lateral interface, as illustrated in Figure 2.7.

### 2.1.5 Wake structure

In the natural aquatic ecosystems, Vandenbruwaene et al. (2011) observed that vegetation often emerges in circular patches during the initial stages of growth. In recent decades, a large number of laboratory experiments (He, Ghisalberti, An, Draper, Branson, Ren & Cheng 2024) and numerical simulations (Nicolle & Eames 2011) have been carried out on the wake flow behind

a circular patch. Relative to a solid obstruction (Castro 1971, Zong & Nepf 2012), porous patches allow a portion of the fluid to penetrate and bleed through. The presence of bleed flow delays the interaction of the two shear layers initiated on both sides of the patch, thereby delaying the onset of the von Karman vortex street (Chang & Constantinescu 2015) and creating a steady wake region (Taddei et al. 2016). Various flow regimes have been identified in the wake, according to patch characteristics and flow shallowness.

Nicolle & Eames (2011) observed three distinct flow regimes downstream of a circular vegetation patch by altering the solid volume fraction ( $\Phi$ , Equation 2.1): (1) a low density regime, for  $\Phi < 0.05$ , in which the individual stem inside the patch behave as isolated cylinders (Figure 2.8a), (2) an moderate density regime, for  $0.05 < \Phi < 0.15$ , in which the cumulative effect of the patch becomes apparent: two shear layers develop and interact at the end of the steady wake region, rolling up to create a von Karman vortex street (Figure 2.8c), and (3) a high density regime, for  $\Phi > 0.15$ , in which the vegetation patch behaves as a solid cylinder with the same diameter: a von Karman vortex street forms at the patch scale directly downstream of the patch (Figure 2.8d). However, He, Ghisalberti, An, Draper, Branson, Ren & Cheng (2024) observed a flow regime that could not be classified within these three regimes. In this regime, unstable shear layers developed separately on both sides of the array. Although large-scale turbulent eddies formed within the separated shear layers, they did not interact and initiate a von Karman vortex street (Figure 2.8b). This behavior arises because the wake structure depends on shallowness, which primarily suppresses wake instabilities and, to a lesser extent, affects the velocity within the patch, in addition to the patch density, which determines the proportion of incident flow that passes through the patch.

In addition to patch characteristics, flow shallowness also plays a significant role in controlling wake structure (Chen & Jirka 1995), as it limits vertical motions, making the wake structure mostly two-dimensional, and inhibits the lateral movement of large-scale oscillations such as vortex shedding. The effect of flow shallowness can be quantified using a non-dimensional wake stability parameter (Chen & Jirka 1995),

$$S = \frac{C_f D}{h} \quad (2.24)$$

where  $C_f$  is the bed friction coefficient,  $D$  is the diameter of the patch,  $h$  is the water depth. This parameter measures the stabilizing effect of bed friction relative to the destabilizing impact of transverse shear on wake instability development (Chu et al. 1991). When the value of  $S$  exceeds a critical threshold,  $S_c$ , the generation of a vortex street is suppressed. Chen & Jirka (1995) observed a critical value of  $S_c = 0.09$  for a porous plate with a solid volume fraction of 0.5 and  $S_c = 0.2$  for a solid obstruction.

Taking the wake stability parameter into account, He, Ghisalberti, An, Draper, Branson, Ren & Cheng (2024) classified the wake structure into four patterns (Figure 2.8) and attributed the

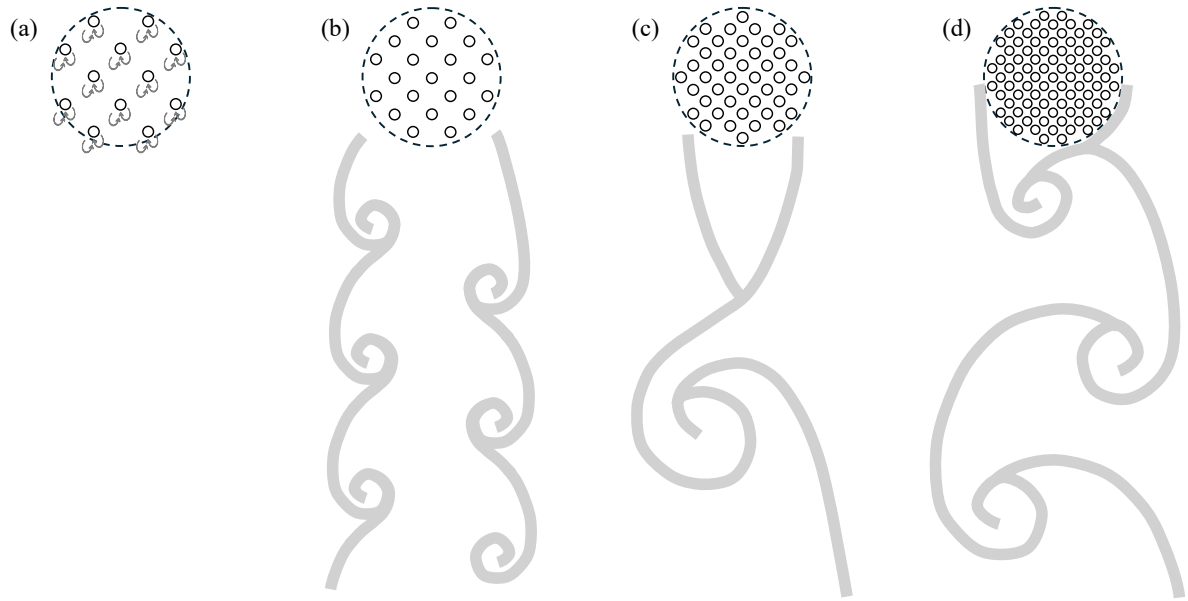


Figure 2.8: Wake behaviors behind an circular vegetation patch. Dashed circle indicates the boundary of the patch. (a) Coupled individual wake, where patch-scale shear layers are stable and the patch wake is dominated by individual element-scale wakes. (b) KH instability wake, where patch-scale shear layers are susceptible to KH instability, but do not generate von Karman vortex street. (c) ‘Steady+shedding’ wake, where a steady wake region presents before the development of a von Karman vortex street. (d) Vortex street wake, where a von Karman vortex street is initiated immediately behind the patch. This figure is adapted from Nicolle & Eames (2011), He, Ghisalberti, An, Draper, Branson, Ren & Cheng (2024).



influence of flow shallowness on wake instabilities to (i) the suppression of the wake instabilities and (ii) the enhancement of the bleeding flow that stabilized the wake. The bed friction increases the velocity of bleed flow by weakening the flow diverted around the array (Creed et al. 2017).

For emergent circular patches, Chen, Ortiz, Zong & Nepf (2012) linked the wake flow structure to a nondimensional flow blockage parameter,  $C_{Da}D$ , which is the ratio of the patch diameter ( $D$ ) and a drag length scale  $(C_{Da})^{-1}$ . The velocity exiting the patch,  $U_{e1}$ , is diminished compared to the upstream velocity,  $U_\infty$ , and this reduction (expressed as  $U_{e1}/U_\infty$ ) becomes greater with increasing flow blockage ( $C_{Da}D$ ). They developed a model to predict,

$$\frac{U_{e1}}{U_\infty} \approx \begin{cases} 1 - 0.21C_{Da}D, & C_{Da}D < 4 \\ 0.16, & C_{Da}D > 4. \end{cases} \quad (2.25)$$

By assuming that the gradient of the normalized velocity after the patch is comparable to the gradient across the patch, Chen, Ortiz, Zong & Nepf (2012) predicted the steady wake velocity,  $U_1$ ,

$$\frac{U_1}{U_\infty} \approx \begin{cases} 1 - \frac{1}{4}C_{Da}D, & C_{Da}D < 4 \\ 0.03, & C_{Da}D > 4. \end{cases} \quad (2.26)$$

Zong & Nepf (2012) predicted the length of the steady wake region,  $L_1$ , by assuming a linear growth of the shear layers on either side of the steady wake region,

$$\frac{L_1}{D} = \frac{1}{4S_1} \frac{1 + U_1/U_2}{1 - U_1/U_2} \approx \frac{1}{4S_1} \frac{1 + U_1/U_\infty}{1 - U_1/U_\infty} \quad (2.27)$$

where  $S_1$  is a constant ( $0.10 \pm 0.02$ ) across a wide range of patch diameters and densities (Zong & Nepf 2012),  $U_2$  is the fastest velocity lateral adjacent to the steady wake region. If the channel is significantly wider than the patch diameter,  $U_2 \approx U_\infty$ , yielding the right-most expression in Eq. (2.27). Note that a delayed initiation of the vortex street is still observed even as the velocity behind the patch is nearly zero, presenting  $L_1/D = 2.5$ . The length of the steady wake region,  $L_1$ , is given by

$$\frac{L_1}{D} = \begin{cases} 2.5 \left[ \frac{8 - C_{Da}D}{C_{Da}D} \right], & C_{Da}D < 4 \\ 2.5, & C_{Da}D > 4. \end{cases} \quad (2.28)$$

However, when  $C_{Da}D$  becomes sufficiently large such that the wake resembles that behind a solid body, a recirculation zone and a vortex street form immediately behind the patch, and  $L_1 \approx 0$  for  $C_{Da}D > 10$ . Furthermore, Li, Wang, Li, Wang & Xu (2025) observed that the steady wake length for emergent patches with a finite width depends on patch width, while for channel-spanning patches, it depends on patch length.

Yu et al. (2021) introduced a length( $L$ )-related flow blockage parameter ( $C_{Da}L$ ) to evaluate

the impact of patch elongation on wake flow and vortex structures. Their experimental results demonstrated that as a patch became denser and/or longer (indicated by an increase in  $C_{Da}L$ ), the steady wake region shortened, and vortices formed closer to the trailing edge of the patch, resulting in greater turbulence after the steady wake region. When the length-related flow blockage reached a critical level ( $C_{Da}L > 8$ ), von Karman vortices were initiated directly behind the patches,

$$\frac{L_1}{b} = \begin{cases} (2.5 \pm 0.5) \left[ \frac{9 - C_{Da}L}{C_{Da}L} \right], & C_{Da}L \leq 8 \\ 0.3 \pm 0.3, & C_{Da}L > 8, \end{cases} \quad (2.29)$$

in which  $b$  is the half width of the vegetation patch.

At the end of the steady wake region, the shear layers converge at the wake centerline, forming a patch-scale von Karman vortex street. Then, the streamwise velocity gradually recovery toward the incoming flow velocity ( $U_\infty$ ). This patch-scale von Karman vortex street oscillates at a characteristic frequency,  $f_{VK}$ . By applying the same scaling as for a solid cylinder with a diameter of  $D$ , the Strouhal number becomes

$$St = \frac{f_{VK}D}{U_\infty}. \quad (2.30)$$

Zong & Nepf (2012) observed  $St \approx 0.2$  behind circular porous patches, consistent with the vortex shedding of a solid cylinder,  $St \approx 0.2$  for  $200 < Re < 3 \times 10^5$  (Roshko 1961, Schewe 1983). For the wake regime dominated by individual elements (Figure 2.8a), Nicolle & Eames (2011) observed that the shedding from individual cylinders within the patch governs the oscillation frequency in the near-wake region, i.e. the individual cylinder diameter set the length scale for vortex shedding. Chang & Constantinescu (2015) observed this constant dimensionless frequency presented in the near-wake regions when the wake billows were absent. In this scenario, the frequency arises from an instability acting on the separated shear layers, leading to in-phase, large-scale undulating deformations of both layers. Furthermore, the channel blockage, i.e., the ratio of the obstruction diameter ( $D$ ) to channel width ( $B$ ), may affect the shedding frequency ( $f_{VK}$ ), or specifically the Strouhal number ( $St$ ) of the wake vortex street. Many previous studies related to circular cylinder reported (Coutanceau & Bouard 1977, Chen et al. 1995, Wang et al. 2021) that  $St$  increase with increasing  $D/B$ .

In contrast to the largely two-dimensional wakes generated by emergent patches of finite-width and submerged channel-spanning patches discussed above, a submerged patch of finite width can induce vortex structures in its wake at both the vertical and horizontal interfaces. As a result, the wake structure behind a submerged patch of finite width becomes three-dimensional (Ortiz et al. 2013, Marjoribanks et al. 2019, Matsumoto et al. 2025). This three-dimensional wake structure grows nonlinearly, which is not reflected by the classical mixing layer theory (Nicolai et al. 2020). The strong down flow observed downstream of the patch contributes

to decaying the interaction of horizontal shear layers (Taddei et al. 2016, Chang et al. 2017, Nicolai et al. 2020, Liu, Huai & Ji 2021). Liu et al. (2018) reveals the impact of patch height ( $H$ ) to width ( $D$ ) aspect ratio on wake structure. Specifically, a horizontal von Karman vortex presents and controls the wake structures for  $H > D$  (Figure 2.3a). In contrast, for  $H < D$ , the von Karman vortex was absent but a vertical recirculation dominated in the patch wake (Figure 2.3b).

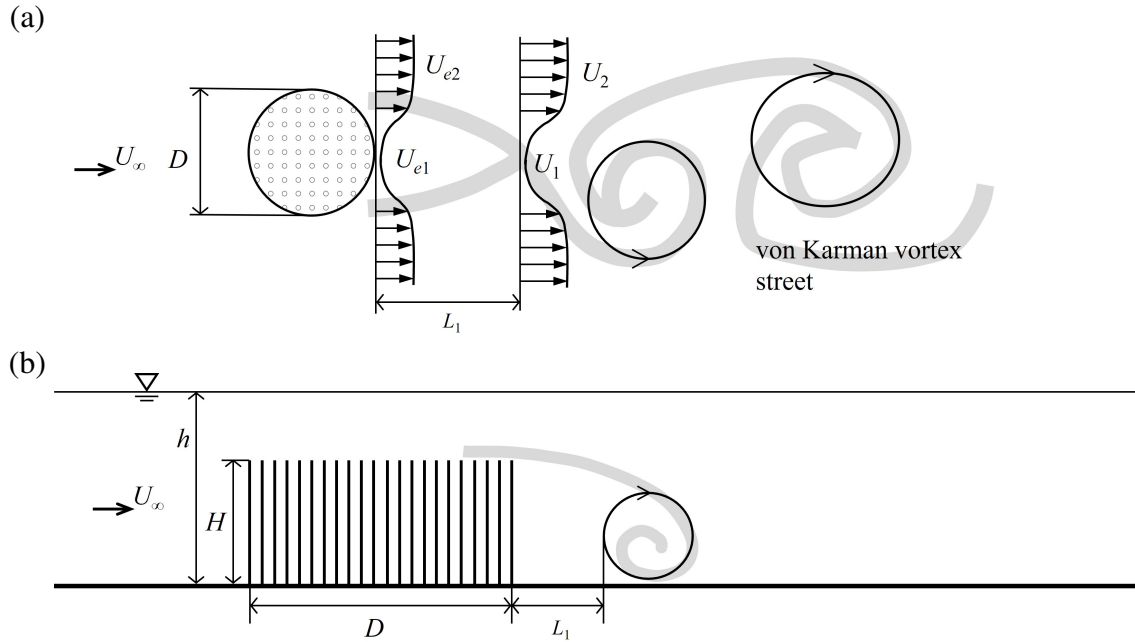


Figure 2.9: (a) Top view and (b) side view of the flow structure behind a submerged, circular patch.  $D$  is the diameter of the patch.  $H$  is the patch height. (a) shows the flow structure when the wake is dominated by the horizontal vortices,  $H > D$ . (b) shows the domination of the vertical vortices in the wake,  $H < D$ . This figure is adapted from Hu et al. (2018).

In addition to the patch height to width aspect ratio, Cornacchia et al. (2022) considered various live submerged vegetation patches and concluded that the patch properties, such as plant species and density, influence the length of the steady wake region. Kitsikoudis et al. (2016) demonstrated that the steady wake length downstream of a tree-like element was shorter than that observed behind a uniform element. This reduction was attributed to enhanced turbulent mixing, driven by vertical shear between the subcanopy and canopy regions. In addition, for the tree-like configuration, the interaction between the subcanopy jet and the lee-wake vortices generated behind the canopy distorted the development of von Karman vortex street. Yagci et al. (2010) experimentally investigated the influence of different forms of natural riparian vegetation on flow structure. They found that the vegetation form of ‘erect’ exhibited more retaining influence over time-averaged mean velocity compared to ‘compressed’ form, which was attributed to the streamlining effect. When the foliages of the plant adapt streamlines

of the flow, effective area for the water passing through vegetation increases. Matsumoto et al. (2025) investigated how the deflection of flexible vegetation elements affected vortex structures. Their experiments revealed that the deflection of these elements in a flexible vegetation patch generates a rotating secondary flow, which facilitates the transportation of momentum into the wake region of the vegetation patch.

Park & Nepf (2025b) investigated how the spatial configuration of submerged patches affects the relative contributions of wake and shear production. They found that at low area densities ( $\Phi < 0.5$ ), wake production dominates over shear production. In contrast, at high area densities  $\Phi > 0.5$ , shear production becomes more significant, owing to the development of an enhanced shear layer at the top of the canopy and a reduction in mean velocity within the patch.

Anjum et al. (2025) examined how the shape of vegetation patches affected wake structures. Their numerical simulations revealed that circular patches offered the maximum flow resistance, resulting in a 25%–30% reduction in mean streamwise velocity in the downstream region, whereas rectangular and square patches lead to a 15%. Additionally, von Karman vortices were observed only behind circular patches and did not occur behind square or rectangular patch shapes.

## **2.2 Sediment transport in vegetated channel**

In aquatic environments, sediment transport is a key factor influencing water transparency and facilitating material exchange between sediments and the overlying water (Black et al. 2002, El Ganaoui et al. 2004). Numerous field studies have demonstrated that vegetation generally reduces sediment concentrations, either by enhancing sedimentation, which is highly dependent on local hydrodynamics (Horppila & Nurminen 2001, Leonard & Reed 2002, Leonard et al. 2006, Pujol et al. 2010), or by directly trapping sediment on stems and leaves (Saiers et al. 2003, Peruzzo et al. 2012). This section reviews the effects of vegetation on sediment transport, with a focus on hydrodynamic processes.

### **2.2.1 Incipient sediment motion**

Reliable prediction of sediment transport in vegetated flows requires quantifying the threshold conditions for sediment motion within vegetated areas. The onset of sediment movement is primarily governed by flow conditions. Specially, when flow intensity surpasses a critical threshold, sediment particles begin to move. In open channel flows, incipient sediment motion is typically characterized by the critical shear stress and critical flow velocity. However, the presence of vegetation significantly alters the flow field. Strong interactions between sediment particles and near-bed flow structures, as well as elevated turbulence levels complicate the

prediction of incipient sediment motion compared to bare riverbeds. Increased near-bed turbulent kinetic energy generated by vegetation is negatively correlated with bottom boundary layer thickness and, ultimately, with bed shear stress (Conde-Frias et al. 2023). On one hand, vegetation introduces additional hydraulic resistance in water flow, reducing both mean velocity and bed shear stress within vegetated areas, thereby inhibiting particle movement (López & García 1998, Nepf 1999, Leonard & Luther 1995, Shi et al. 1995, Pujol et al. 2010), which inhibits the particle movement. On the other hand, vegetation can also enhance turbulence intensity, particularly in the presence of sparse vegetation, due to increased turbulence production from stem wakes (Ninto & Garcia 1996, Nepf 1999, Vollmer & Kleinhans 2007, Celik et al. 2010, van Katwijk et al. 2010). Recent studies have demonstrated the dominant role of turbulence in the local entrainment of sediment particles (Ali & Dey 2017, Shih & Diplas 2018, Li & Katul 2019, Deitrick et al. 2023). Given the difficulties in predicting incipient sediment motion using bed shear stress in vegetated flows, critical flow velocity is often considered a more efficient and effective parameter, and is widely applied in practice.

Within vegetated areas, spatial heterogeneity in flow (Nepf 2012a) leads to spatial variation in the incipient motion of sediment particles, which is governed by local flow conditions (Cheng et al. 2020). This behavior is analogous to the patterns observed around piers (Escalaiaza & Sotiropoulos 2011). For example, Bouma et al. (2007) found that sediment initiation near vegetative stems was closely associated with localized increases in velocity, leading to the formation of scour holes around individual stems.

With rigid emergent vegetation, Cheng et al. (2020) predicted the critical flow velocity for incipient sediment motion by incorporating both mean flow and turbulence effects into the force balance equation, using a spatiotemporal averaging approach. They also found that, for rigid emergent vegetation, the critical flow velocity is independent of flow depth, consistent with the observations of Tang et al. (2013). In a related study, Yang et al. (2016) proposed a turbulent kinetic energy ( $k_t$ ) model to predict sediment resuspension, based on the assumption that near-bed  $k_t$  sets the threshold for sediment resuspension. In this framework, the near-bed  $k_t$  is considered as the sum of turbulent kinetic energy generated by both the river bed  $k_{t(\text{bed})}$  and vegetation  $k_{t(\text{veg})}$ ,

$$k_t = \underbrace{\frac{\tau}{0.19\rho}}_{\text{bed-generated}(k_{t(\text{bed})})} + \underbrace{\delta_{k_t} [C_D \frac{\Phi}{(1-\Phi)\pi/2}]^{2/3} U^2}_{\text{vegetation-generated}(k_{t(\text{veg})})}, \quad (2.31)$$

where  $\delta_{k_t}$  is a scale constant, with  $\delta_{k_t} = 0.4 \pm 0.3$  for an array with a single diameter of  $d = 0.6$  cm (Yang & Nepf 2019) and  $\delta_{k_t} = 0.52 \pm 0.07$  for an array with a varying diameter of  $d = 0.64 \sim 2.5$  cm (Zhao & Nepf 2021). Based on this model, the critical flow velocity of the

incipient sediment motion ( $U_c$ ) can be predicted by

$$\frac{U_c}{U_\infty} = \frac{1}{\sqrt{1 + C\Phi^{2/3}}}, \quad (2.32)$$

where the coefficient  $C = 0.9C_D^{2/3}/C_f$ , with  $C_f$  the bed friction coefficient and  $C_D$  the canopy drag coefficient. Although this model is only applicable to sparse emergent vegetation ( $d/\Delta S \leq 0.25$ ), it offers a unified framework for describing incipient sediment motion over both bare beds and vegetated channels.

With rigid submerged vegetation, Xue et al. (2017) developed an empirical model to predict the critical flow velocity for incipient sediment motion, based on the average flow velocity below the vegetation height, instead of using the bulk velocity over the entire water depth. Wang et al. (2015) observed that the critical velocity for sediment motion increases as plant density decreases, and as water depth and sediment grain size increase. Additionally, they found that the critical velocity is higher for submerged flexible plants compared to rigid vegetation. Similarly, Zhang, Mi, Wang, Li, Li, Xu, Li, Wang & Wu (2024) emphasized that the incipient velocity is highly influenced by vegetation density and relative submergence. Specially, a higher relative submergence or/and a lower vegetation density lead to a greater critical velocity (Wang, Li, Yang & Huai 2022). However, at very high densities, increased vegetation resistance can actually inhibit sediment motion.

Sediment characteristics also play a critical role in sediment motion. Smaller, lighter particles are more easily mobilized than larger, heavier ones. Many previous works have reported that vegetation-generated turbulence can enhance erosion rates and lower the velocity threshold required for the erosion of non-cohesive sediments. However, in natural aquatic ecosystems, sediments are often cohesive. Deitrick et al. (2024) investigated whether vegetation-generated turbulence has a similar effect on natural cohesive sediments. Their experimental results showed that, at the same flow velocity, cohesive sediments exhibited higher turbulent kinetic energy compared to non-cohesive sediments. However, vegetation-generated turbulence did not increase bed stress or the resuspension rate for cohesive sediments relative to non-cohesive sediments. It was hypothesized that the short time-scale fluctuations characteristic of vegetation-generated turbulence were insufficient to overcome the cohesive forces between sediment grains, thereby explaining why increased turbulence did not affect the erosion threshold or rate for cohesive sediments.

### 2.2.2 Sediment transport rate

Bedload transport rates are closely linked to sediment motion in the near-bed region. Turbulence enhances the mobility of individual particles (Liu, Shan & Nepf 2021, Tinoco & Coco

2018), thereby increasing the channel-averaged sediment transport rate (Yang & Nepf 2018, 2019, Tseng & Tinoco 2021). Vegetation contributes to turbulence generation both in the wakes of individual stems and branches (Nepf 2012*b*), and within the shear layer that forms between low-discharge vegetated regions and high-discharge open regions (Monti et al. 2020, Akao et al. 2022). The magnitude and spatial distribution of vegetation-generated turbulence depend on several factors, including stem area density (Tanino & Nepf 2008*b*), stem diameter (Zhao & Nepf 2021), the degree of clustering (Sukhodolov & Sukhodolova 2010), and branching morphology (Maza et al. 2017, Xu & Nepf 2020).

To examine the influence of stem diameter and arrangement on bedload sediment transport, Zhao & Nepf (2021) conducted laboratory flume experiments using arrays with varying and mixed stem diameters. Their results showed that the bedload transport rate was governed by turbulent kinetic energy and was independent of stem diameter. Similarly, Mu & Fu (2023) reported that stem diameter and stem arrangement did not strongly influence the relationship between sediment transport capacity and flow velocity. They concluded that flow velocity alone could account for the effects of stem diameter and arrangement on sediment transport capacity.

To consider the influence of plant morphology on turbulence and bedload transport, Zhao & Nepf (2021) incorporated a plant-specific morphology ratio into Equation 2.31 to predict turbulence as a function of biomass and velocity. Liu, Shan, He, Li, Liu & Nepf (2024) observed that when the frontal area of plants increased with height above the bed, near-bed velocities were higher than those predicted using a depth-averaged frontal area. In addition, He, Shan, Liu, Cao, Liu & Guo (2024) found that plant morphology can lead to considerable differences in transport rates compared to the assumption of uniform morphology. To address this, Liu, Shan, He, Li, Liu & Nepf (2024) proposed a plant morphology coefficient to quantify the vertical variation in frontal area, which improves the predictions of near-bed velocity, turbulence, and bedload transport rates.

To examine the influence of vegetation patchiness on channel-averaged turbulence and sediment transport, Shan et al. (2020) conducted experiments demonstrating that, for a given channel velocity, the greatest levels of turbulence and bed load transport occurred when vegetation was distributed uniformly at random. As vegetation stems became increasingly clustered, with smaller patch diameters and a reduced fraction of the bed area occupied by stems, both turbulence and bed load transport were observed to decrease. Park & Nepf (2025*a*) performed laboratory experiments to evaluate the influences of patch area densities ( $\phi_p$ , the fraction of bed area covered by patches) and spatial configurations of a patchy submerged canopy on bedload transport, including channel-spanning patches and laterally unconfined patches. Specially, at low area densities ( $\phi_p < 0.3$ ), an increase in  $\phi_p$  resulted in more flow passing over the canopy, reducing the near-bed velocity. However, turbulent wakes formed around individual patches, enhancing near-bed turbulent kinetic energy. In this scenario, these competing effects resulted

in only a slight reduction in bedload transport rate as  $\phi_p$  increased. Conversely, at high area densities ( $\phi_p > 0.3$ ), both near-bed velocity and turbulent kinetic energy diminished with increasing  $\phi_p$ , causing a significant reduction in bedload transport rate. What's more, for a given  $\phi_p$ , channel-spanning patches produced less bedload transport than laterally unconfined patches, as the former configuration led to lower near-bed velocities due to the banded distribution of vegetation.

For submerged canopies, the vertical shear layer developed at the top interface enhances the shear production of turbulence (Raupach et al. 1996, Liu et al. 2025). To examine how canopy-scale turbulence affects sediment transport, Zhao & Nepf (2024) performed laboratory experiments using submerged canopies of rigid model vegetation with varying canopy density ( $aH$ ) and submergence ratio ( $h/H$ ). They observed that, for  $h/H < 2$ , the near-bed turbulent kinetic energy ( $k_t$ ) was primarily generated by the stems. In this regime, both near-bed  $k_t$  and bedload transport rate increased with increasing  $aH$ . In contrast, for  $h/H > 2$ , the near-bed  $k_t$  became independent on  $aH$  and  $h/H$ , as a balance was established between decreasing stem-generated turbulence and increasing canopy-scale turbulence with increasing  $aH$  and  $h/H$  (King et al. 2012, Zhang et al. 2020). However, the near-bed velocity decreased with increasing  $aH$  and  $h/H$ , leading to a decline in bedload transport rate even when near-bed  $k_t$  remained constant. Lu et al. (2024) observed that bedload transport rates decreased with increasing submergence ratio, which is attributed to the reduction in near-bed velocity at higher submergence ratios.

To investigate the impact of plant flexibility, Liu et al. (2025) compared the near-bed conditions within flexible and rigid canopies under the same canopy density ( $aH$ ) and submergence ( $h/H$ ). Although the near-bed velocity is similar, the near-bed turbulence and sediment transport rates are lower within flexible canopies compared to rigid ones. In the natural scenario, flexible canopies bend with increasing channel velocity, which effectively reduces their submergence ratio relative to rigid canopies with the same stem density. This results in weaker near-bed velocity, turbulence, and sediment transport within the flexible canopies. At high canopy submergence, turbulence generated in the canopy shear layer enhances near-bed turbulence, partially offsetting the reduction in stem-induced turbulence and increasing sediment transport. Nevertheless, this effect is less pronounced for flexible canopies than for rigid canopies.

## 2.3 Sediment pattern in vegetated channels

Two main approaches have been applied in earlier studies to explore sediment distribution in laboratory experiments. One approach involves fully mixing sediments with water in the source tank, while the other entails paving a layer of sediments on the bottom of the flume. The former method is particularly relevant to studies of net sediment deposition. The latter approach characterizes the sediment deposition and erosion at the same time. The sediments paved at the



channel bottom will adjust as a response to the flow structure.

### **2.3.1 Net deposition pattern in rigid bed**

Aquatic plant enhances net deposition by creating favorable flow structures. For example, for circular emergent vegetation patches, Chen, Ortiz, Zong & Nepf (2012) observed increased net deposition downstream of the patch and attributed this enhancement to reduced velocity and weak turbulence within the steady wake region, which promotes patch elongation (Sand-Jensen & Madsen 1992). Compared to rigid patches, Matsumoto et al. (2025) found that flexible vegetation patches resulted in greater net sediment deposition downstream. This enhancement was linked to secondary flows generated around the flexible patches, which increased lateral sediment transport across patch boundaries. Conversely, Ortiz et al. (2013) reported that strong vertical circulation developed after a flexible, submerged vegetation patch of finite width, increasing turbulent kinetic energy directly downstream and thereby preventing increased deposition in the wake. These findings suggest that flexible submerged patches may be much harder to expand spatially, as adverse feedback inhibits patch growth. Furthermore, de Lima et al. (2015) and Yamasaki et al. (2021) observed that pairs of side-by-side circular patches created an area of enhanced deposition along the centerline between them, with this area extending significantly farther downstream than the region of increased deposition found behind a single patch. As patch density increased or the gap between patches decreased, the minimum wake velocity was further reduced, leading to even greater deposition (Meire et al. 2014). These findings suggest that interactions between patches can promote streamwise growth, depending strongly on wake flow conditions. Ultimately, deposition along the centerline can cause adjacent patches to merge, thereby facilitating lateral expansion of the patches.

On the other hand, aquatic vegetation can mitigate net deposition by generating turbulence. For example, near the leading edge of the meadow, net deposition was reduced compared to the bare bed, primarily due to an up-moving flow associated with flow adjustment (Follett & Nepf 2018) and elevated turbulent kinetic energy generated by the stems (van Katwijk et al. 2010, Deitrick et al. 2023). In the fully developed region of a submerged seagrass meadow (Zhang et al. 2020), net deposition decreased as vegetation density decreased and channel velocity increased, transitioning from being greater than to less than that observed on a bare bed. In particular, lower net deposition was attributed to resuspension induced by stem-scale turbulence, which intensified with lower meadow density and shallower submergence (Zhang et al. 2020). In the wake region of a finite vegetation patch, the initiation of wake vortex street highly enhances the turbulence, reducing net deposition. Kim et al. (2018) identified three distinct deposition patterns in the wake region of an emergent circular patch: (1) for patches with low flow blockage, deposition in the wake region occurred over an extended distance; (2) for patches with intermediate flow blockage, vortex street was developed, resulting in enhanced deposition both

directly downstream of the patch and within the recirculation region; (3) for patches with high flow blockage, enhanced deposition was confined solely to the recirculation region. Overall, the extent of enhanced deposition in the wake region closely linked to the length scale of vortex formation. Downstream of the steady wake region, deposition was suppressed by elevated turbulence levels generated by patch-scale vortices.

Xu, Esposito, Beltrán-Burgos & Nepf (2022) observed competing effects of vegetation density on net sediment deposition in deltaic marshes. Specifically, as vegetation density increases, flow velocity diminished, which (i) restricts sediment supply to the marsh, and (ii) minimizes sediment resuspension. These opposing impacts in sediment supply and retention result in a nonlinear relationship between sedimentation and vegetation density, with maximum sedimentation occurring at an intermediate density. In addition, two distinct patterns of sedimentation were identified. (1) When the resuspension is suppress, the deposition is distributed exponentially, with the highest sediment accumulation at the marsh edge. (2) Conversely, if resuspension presents, particles deposited near the edge may be lifted and transported further into the marsh, leading to reduced sediment accumulation at the edge and a more uniform pattern of net deposition deeper within the marsh.

While vegetation can create favorable conditions for sediment deposition, an adequate sediment supply is also essential for deposition to occur (Västilä et al. 2016, Box et al. 2019). For instance, Liu & Nepf (2016) and Liu et al. (2022) reported that deposition within a vegetation patch only occurred when sediment was resuspended in the channel and stem-scale turbulence within the patch was absent. In these cases, particles resuspended from adjacent areas became available to settle in the wake of the vegetation. Shi et al. (2016) identified three deposition patterns as the ratio of channel shear velocity ( $u_*$ ) to critical shear velocity ( $u_{c*}$ ) changes: (1) a uniform high net deposition when  $u_*/u_{c*} < 0.7$ , in which the shear velocity throughout the channel remains below the critical threshold, preventing resuspension; (2) a uniform low net deposition when  $u_*/u_{c*} > 3$ , in which resuspension occurs throughout the channel; (3) a distinct spatial pattern of net deposition when  $u_*/u_{c*} \approx 0.7$  to 3, in which higher net deposition is observed in the wake of the vegetation patch compared to adjacent areas. Notably, highest net deposition in the wake occurs under this scenario, as resuspension in adjacent regions increases the availability of particles for deposition in the wake. This finding was corroborated by a numerical study conducted by Kim et al. (2018). Furthermore, they proposed that particle characteristics, such as size and density, as well as flow conditions change the sediment pattern by influencing  $u_*/u_{c*}$ . Specially, a low  $u_*/u_{c*}$  corresponds to low velocity or large, heavy particles.

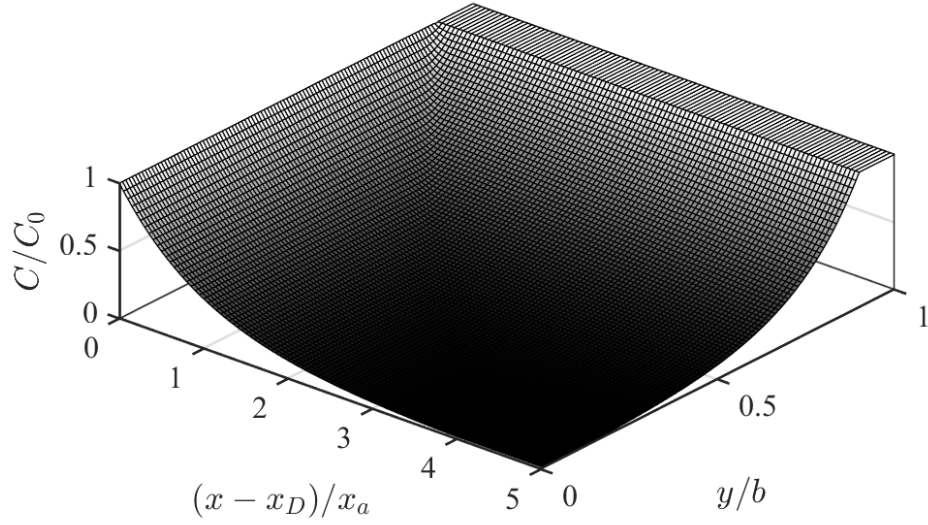
Similarly, Sun et al. (2023) observed distinct deposition patterns in partially vegetated channels depending on sediment supply. Specifically, when no resuspension occurred in the bare region, the distribution of net deposition was uniform inside and outside the vegetated region. As

mean channel velocity increased without inducing resuspension, local vegetation-induced turbulence elevated near-bed turbulent kinetic energy near the leading edge of the canopy, forming a region of diminished deposition. When the mean channel velocity was sufficient to resuspend the sediment in the bare region, mitigated deposition was observed near the leading edge region of the canopy due to elevated near-bed turbulent kinetic energy. However, suspended sediment from the bare channel and the leading edge region could be transported further into the canopy and deposited in areas where the near-bed turbulent kinetic energy was below the critical threshold for resuspension. Zong & Nepf (2011) identified two sources of sediment flux to an along-bank emergent vegetation patch: (1) advection of particles across the leading edge, and (2) lateral dispersion of particles from the adjacent open region (Figure 2.10). The relative contribution of these two supplies governs the spatial distribution of net deposition within the vegetated zone. Initially, advection dominates the sediment supply, in which net deposition increases downstream as local velocity decreases (Zong & Nepf 2010, Yang et al. 2021). This trend is associated with reductions in both vertical velocity and turbulent kinetic energy, with deposition peaking near the adjustment length (Zhang et al. 2020). In this region, the deposition is laterally uniform, revealing the uniform mean flow that delivers sediment. Beyond this region, deposition decreases in the streamwise direction because of the continuous depletion of suspended sediment in the water column (Zong & Nepf 2010). In contrast, net deposition is highest near the streamwise interface of the patch and decays laterally inward, indicating the influence of dispersive transport from the patch edge. Lateral dispersion is driven by two processes, both related to the formation of shear-layer vortices at the interface between the patch and the open channel. By producing turbulence, these vortices promote greater turbulent diffusion of sediment. Additionally, the movement of vortices induced wave oscillations in the flow field, transporting the sediment further into the patch.

Liu, Shan & Nepf (2021) reported that the turbulent kinetic energy increased with increasing velocity and vegetation density, but was independent of stem diameter. For a given sediment size, both vegetated and bare beds shared the same threshold of turbulent kinetic energy for resuspension, so higher vegetation density corresponded to a lower critical velocity. It was observed in this study that both the critical turbulence and the critical velocity for resuspension were independent of stem diameter.

Considering both bed-generated and shear-generated turbulence, Gui, Shan, Li, Sun & Liu (2024) found that near-bed turbulent kinetic energy in floating vegetation canopies increases with higher channel-average velocity, greater vegetation density, and/or reduced relative flow depth. When the near-bed turbulent kinetic energy exceeds the threshold for resuspension, net deposition below the vegetation canopy decreases compared to an upstream reference site.

(a)



(b)

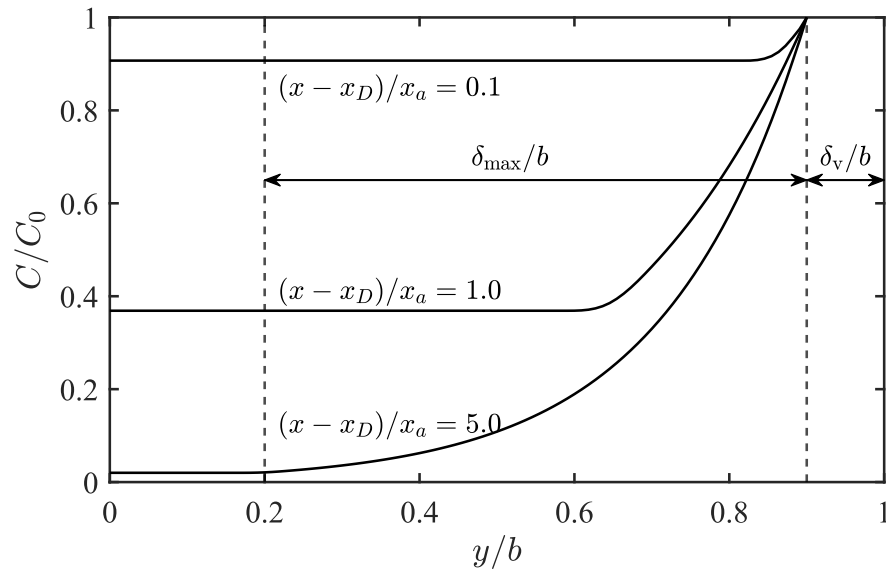


Figure 2.10: Sediment flux to an along-bank emergent vegetation patch. The suspended particle concentration  $C(x, y)$  is normalized by the upstream concentration  $C_0$ .  $x_D$  is diverging region in the vegetation patch.  $x_a$  is the advection length scale.  $b$  is the width of the vegetation patch.  $\delta_v$  is penetration thickness of the shear layer into the patch, in which the particle concentration is the same as the free stream,  $C_0$ .  $\delta_{\max}$  is the diffusion length scale, which is defined as the maximum distance particles can be delivered from the streamwise interface by lateral dispersion. (a) Simulated suspended particle concentration in the vegetation patch at  $x > x_D$ . (b) Simulated lateral concentration profiles across the patch width ( $0 < y < b$ ). This figure is adapted from Zong & Nepf (2011).

### 2.3.2 Bedform development in mobile bed

By affecting the dynamic between water flow and sediment transport, vegetation can produce localized changes in bed elevation, driving the evolution of channel morphology over time (Oorschot et al. 2016). Specifically, vegetation elements increase hydraulic resistance, reducing flow velocity and promoting sediment deposition (Klösch & Habersack 2017), thereby raising bed elevation. The presence of vegetation stabilizes the riverbanks by binding the soil with roots and enhancing cohesion with the addition of organic material (Simon & Collison 2002, Li, Chiu & Chen 2025). In contrast, the enhanced turbulence generated by vegetation can lead to sediment loss, lowering the bed elevation, reducing bank stability (Rinaldi & Casagli 1999, Li et al. 2023), and leading to vegetation uprooting (Edmaier et al. 2015). Field surveys showed that dense vegetation patches promoted mid-channel and point bar accretion by facilitating deposition (Gurnell et al. 2008, 2012). Vegetated bars were often multi-threaded with complex microtopography, in contrast to the simpler, single-thread bars found in non-vegetated areas (Gurnell et al. 2008). Experimental studies have demonstrated that uniform vegetation on floodplains can shift rivers from having multiple channels to a single, unified channel (Tal & Paola 2010, van Dijk et al. 2013).

Kim, Kimura & Shimizu (2015) identified distinct bedform patterns surrounding a finite patch of vegetation under varying incoming flow conditions relative to the sediment motion threshold. Specifically, when flow remained below the threshold, the most pronounced erosion was observed opposite the patch and near its leading edge. In contrast, when flow conditions exceeded the threshold for sediment motion, sediment deposition occurred both within and around the patch, attributed to the reduced bed shear stress. Furthermore, Tranmer et al. (2024) reported that bed deposition and erosion were also affected by the quantity of sediment delivered from upstream. Specifically, erosion occurred in the channel areas adjacent to the patch regardless of sediment supply, while deposition within the patch interior was mitigated under low sediment supply and enhanced when sediment supply was high. Consequently, higher reach-scale sediment supply may promote greater topographic diversity in alluvial systems (Yarnell et al. 2006, Pfeiffer et al. 2019).

Within the vegetated region, Yager & Schmeeckle (2013) observed that vegetation elements generate spatial variations in bed load fluxes, resulting in distinct scour zones adjacent to the stems (Kim et al. 2019) and depositional dunes between them. The observed spatial variation was attributed to changes in near-bed turbulence levels and the influence of coherent structures. In addition, Penna et al. (2022) observed that, within low-density vegetation patches, stem-induced scour holes and depositional dunes tend to be elongated and aligned with the flow direction, indicating that sediment transport primarily occurs longitudinally. However, as flow discharge decreases and flow intensity diminishes, slight sediment dispersion presents laterally. With increasing vegetation density, the elongated dunes become shorter and expand laterally,

a result of the increased obstruction from stems, which promotes both streamwise and cross-stream sediment transport. Within a partially covered submerged vegetation patch, Liang et al. (2025) found that the magnitude of local scouring around the stems decreased as the density and width of the vegetation patch increased, which was attributed to mitigated flow intensities.

Near the leading edge of the patch, erosion is widely observed, mainly caused by the significant turbulence and strong flow diversion (Follett & Nepf 2012, Kim, Kimura & Shimizu 2015). The high turbulence initiates the sediment motion. Then, the lateral flow diversion carries a part of the eroded sediment out of the patch. The rest of the eroded sediment flows downstream, creating a depositional dune in the downstream part of the vegetation patch (Le Bouteiller & Venditti 2014, Tinoco & Coco 2016, Chen, Chan & Li 2012) or behind the patch (Gu et al. 2019), as shown in Figure 2.11a. This deposition mound inside the vegetation patch has been observed in finite patches along a side wall (Kim, Kimura & Shimizu 2015) and in submerged patches which cover the full width of the flume (Chen, Chan & Li 2012, Le Bouteiller & Venditti 2015, Tinoco & Coco 2016). In these previous cases, the extent of scour and deposition, such as the volume of scour and deposition inside the patch, and the characteristic lengths of the scour and deposition, including scour depth, dune height, length of the scour hole, horizontal distance of the maximal scour depth, and horizontal distance of the dune crest increased with decreasing array density, which was attributed to the higher velocity and turbulence inside the patch at the leading edge.

For instream finite vegetation patches (Wang, Li & Yang 2023), the sediment pattern exhibits behavior similar to that around a solid obstruction (Dargahi 1990, Kirkil et al. 2008, Yagci et al. 2017). Enhanced flow intensity leads to erosion around the patch (Kalidindi & Khosa 2024). A higher patch density produced a stronger erosion (Neary et al. 2012, Yu, Wang & Liu 2019). In the wake region, the bedform development was usually associated with the initiation and strength of patch-scale von Karman vortex street (Follett & Nepf 2012, Gu et al. 2019). Follett & Nepf (2012) investigated sediment patterns related to an emergent circular patch exposed to incoming flow above the threshold for sediment movement. The sediment patterns in the wake region varied with the patch flow blockage. For a high flow-blockage patch, the von Karman vortex street in the patch wake directs deposition to the centerline of the wake. However, for a low flow blockage patch, the von Karman vortex street is weak or absent, and deposition does not occur at the wake centerline, but instead, deposits along the sides of the wake. Furthermore, despite notable sediment redistribution around the patches investigated, net deposition was not detected at the reach scale.

In contrast to an emergent finite patch, Gu et al. (2019) considered the influence of the submergence ratio of an instream finite patch on bedform formation. For deeply submerged patches, a region of net deposition was observed in the wake. In contrast, for slightly submerged and emergent patches, scouring presented both in the wake and in adjacent areas. This eroded

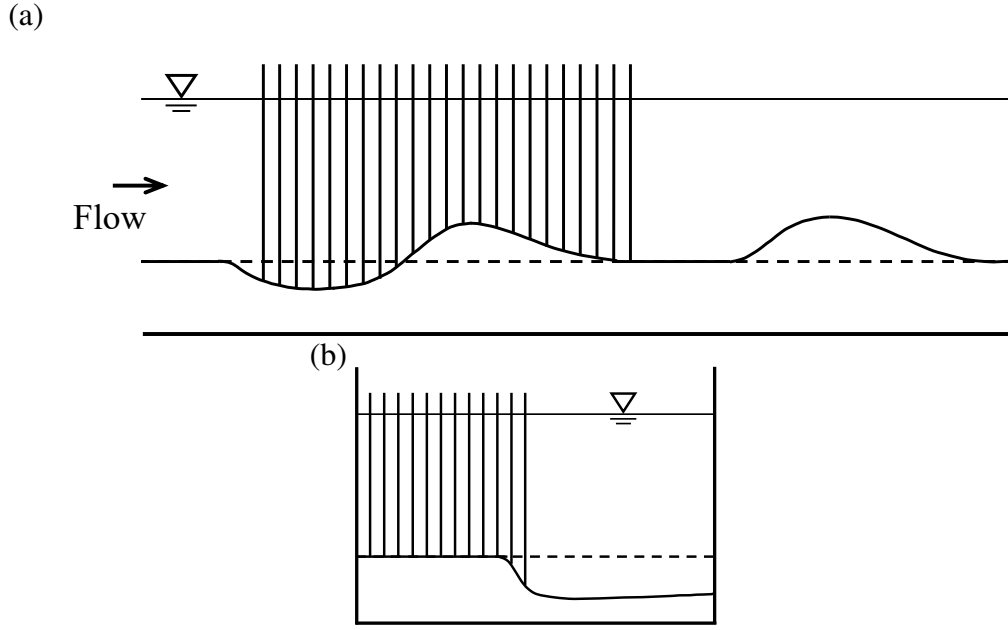


Figure 2.11: (a) A side view of longitudinal bed elevation associated with a vegetation patch. (b) A front view of lateral bed elevation associated with a finite vegetation patch, with a patch width smaller than the channel width. The dashed line indicates the bed elevation before exposure to the water flow.

sediment facilitated sediment deposition in the wake. However, the amount of net deposition was less than that of erosion. What's more, in the adjacent regions, the most significant scouring was closely linked to the submergence ratio and density of the patch, with higher submergence ratios and patch densities leading to increased net erosion.

The depositional mound in the wake creates favorable conditions for vegetation growth, making the patches elongated streamwisely (Gurnell 2014). To account for different growth stages of an instream vegetation patch, experiments by Yagci et al. (2024) demonstrated that both the volume of scour and the height of the wake mound increase as the patch extends downstream and its density increases. In this scenario, the depositional mound becomes more localized due to a reduced bleed flow and enhanced lateral mixing, which leads to the early onset of a von Karman vortex street. Consequently, for dense and elongated patches, the early recovery of flow in the wake zone shortens the deposition length, ultimately limiting the spread of the deposited mound in the wake zone. This phenomenon provides insight into why vegetation patches in streams tend to have restricted longitudinal expansion.

For a near-bank vegetation patch, the elevated turbulence near the lateral interfaces of the patch as well as the enhanced mean flow at the adjacent bare region contribute to the sediment erosion (Temmerman et al. 2007, Bennett et al. 2008, Guan & Liang 2017, Xu et al. 2019, Kumar et al. 2025, Kumar & Sharma 2025a,b), which constraints the lateral growth of the patch (Figure 2.11b). Rominger et al. (2010) observed that regions where the Shields parameter ra-

tio exceeded unity corresponded to areas of erosion, while regions with a ratio less than unity were associated with deposition. The Shields parameter ratio quantifies the balance between destabilizing forces (drag forces) and stabilizing forces (setting forces) acting on cohesionless sediment. Li et al. (2024) observed that the maximum depth and length of the erosion region in the adjacent bare region increased with increasing patch length, and achieved constant until the patch length is over the flow adjustment length. In contrast, Yan et al. (2023) found that increasing the length and density of the patch caused the point of maximum erosion depth to migrate upstream. Near the lateral interface of the patch, Kim, Kimura & Shimizu (2015) observed a depositional ridge, which is consistent with field observations during a flood reported by Rodrigues et al. (2006) and Euler et al. (2014). This depositional ridge elongated downstream. Yan et al. (2023) observed that the elongated ridge for a long patch shifted to a short-point ridge for a short patch. For channel-spanning submerged vegetation patches, bedform pattern varies with densities and patch length (Song, Liu, Yang, Li, Cai, Feng, Huang, Hao, Li, Zhan & Wen 2024).

For vegetated alternate bars, the flow was redirected toward the non-vegetated side of the flume, leading to sediment erosion (Habib & Tanaka 2025). In addition, the vegetated bars enhanced sediment deposition by slowing the flow both inside and downstream of the vegetation patches. Sediment accumulation downstream suggested the migration of vegetated bars and bar elongation (Vargas-Luna et al. 2019, Jourdain et al. 2020). Over time, vegetation on bar tops contributed to a more stable channel morphology. Despite ongoing channel dynamics, the opposing processes of bank erosion and local bank accretion balanced each other, maintaining overall morphological equilibrium.

Ripples were created within a channel-spanning vegetation patch (Yang & Nepf 2019). For low solid volume fraction ( $\Phi \leq 0.012$ ), stem spacing constrained the ripple wavelength and the presence of model vegetation accelerated ripple migration. However, when the solid volume fraction increased to  $\Phi = 0.025$ , ripple height approached the grain size and distinct ripples were absent, indicating a shift to sheet flow, where sediment is transported over a flat bed without bedform development. Additionally, ripple migration-caused bed load transport decreased as  $\Phi$  increased, revealing that plants promote the onset of sheet flow. In addition, in a partially covered submerged vegetation patch, Liang et al. (2025) reported that the turbulent kinetic energy outside the vegetation three times higher than those within the patch. This significant increase in turbulence greatly influenced bedform development and led to an increase in roughness height. Bedform characteristics, such as ripple length and steepness, were found to be inversely correlated with the strength of near-bed turbulent kinetic energy.

The plant morphology also influenced the bedform development by affecting the flow structure (Zhang et al. 2016). For instance, Yagci et al. (2016) and conducted experimental research to examine sediment pattern around various forms of individual vegetation elements. Their



study revealed that intact plant forms created two elongated scour holes downstream with a distinct ridge. In contrast, the impermeable form of the plant resulted in localized scour, increased deposition, and brought the deposition zone closer to the plant. Additionally, the study demonstrated that bending reduced the projected area of the plant while increasing its bulk volume, thereby reducing scour compared to the intact form. Consequently, the scour zone became more elongated and extended further downstream. Artini et al. (2024) demonstrated that leafy vegetation significantly altered bed morphology, reducing the average dune wavelength and promoting the development of complex three-dimensional geometries. Their experiments also highlighted that the bed-load transport rate increased in the presence of leafy, flexible vegetation with a larger frontal area, due to the enhanced turbulence generated by the vegetation. Similarly, Suresh et al. (2025) examined how the aspect ratios of flexible blade (length-to-width ratio) influenced sedimentary bed morphology. They found that changes in velocity magnitude were strongly influenced by the posture of the flexible blade. At a given flow velocity, blade with lower aspect ratios experienced less deformation, resulting in greater near-bed velocity in the wake deflection zone and increased erosion volumes. Furthermore, when the blade experienced minor deformation, the pronounced velocity increase near the bed was attributed to substantial flow deflection at the blade's sides and intensified mixing with high-momentum overlying flows.

To examine how the spatial distribution of vegetation affects channel morphological evolution, Li, Claude, Tassi, Cordier, Vargas-Luna, Crosato & Rodrigues (2022) developed a numerical model that considers two commonly observed vegetation patterns: (a) the filled pattern, characterized by plants well distributed within the patch, and (b) the stripe pattern, where plants only are aligned only along the patch contour. The numerical results revealed that the stripe pattern led to channel widening, increased slope, and reduced water depth in an alternate bar system, accompanied by higher sediment transport rates. While the filled pattern produced similar effects, they were less pronounced. Additionally, the stripe pattern caused alternate bars to migrate toward the channel centerline, resulting in the formation of center bars. Scroll bars that developed downstream were shorter and associated with less distinct chute channels compared to those formed under the filled pattern. Despite having much lower vegetation coverage, the stripe pattern reduced bar elongation rates in a manner similar to the filled pattern.

In addition to flow conditions and plant characteristics, the development of bedform is highly connected to the characteristics of sediment particles (Debnath et al. 2012, Sun et al. 2023). Under identical flow conditions, small, light particles are more likely to be resuspended compared to large, heavy particles. In particular, Lee & Sturm (2009) found that scour depth around bridge piers diminished with increasing bed grain size relative to pier diameter. This relationship arose because coarser grains generally had higher critical shear stresses, making them more resistant to erosion compared to finer sediments. In contrast, larger obstructions

can generate increased local turbulence, enhancing the potential for sediment motion. In addition, Okhravi et al. (2023) developed a numerical model to explore how sediment mixtures affect sediment deposition patterns around four aligned circular piles. Their simulation results revealed significant differences in the shape of scour holes and sediment deposition mounds between uniform and non-uniform sediments. These variations were attributed to armoring effects, where finer particles are more readily transported, while coarser particles remain on the bed surface and form clusters. This armor alters the flow field, ultimately leading to a distinct equilibrium sediment pattern. Baas et al. (2013) found that ripples formed on cohesive, mixed sand–mud beds with bed mud fractions of up to 18% were significantly smaller than equivalent bedform on non-cohesive sand beds. Furthermore, the bedform height exhibited a strong inverse relationship with the initial bed mud fraction (Debnath et al. 2012).

### **2.3.3 The flow response to the morphological change**

The former section demonstrated that channel morphological changes are closely linked to both the flow field and sediment characteristics. Conversely, the resulting bedform can significantly influence flow dynamics (Jerolmack & Mohrig 2005, McKenna Neuman & Bédard 2015, Chakraborty & Sarkar 2016) as well as the growth of vegetation (Larsen & Harvey 2010). For example, sediment movement leads to a change of the bed elevation, modifying the boundary shape. Yi et al. (2022) found that as bedform developed within a vegetated channel, the interior flow within the vegetation canopy adjusted more rapidly, resulting in a shorter flow adjustment length. This acceleration was caused by the sloping bed topography in the adjacent open region. Furthermore, near the lateral edge of the canopy, the deformed bed was observed to weaken the horizontal shear structure. Similarly, Branß et al. (2022) reported that bedform can modify the turbulent structure at the main channel–floodplain interface, enhance sediment entrainment into suspension, and thereby promote levee formation. The formation of levees constrains the lateral transport of water and sediment into the marsh (Belliard et al. 2015), channeling these fluxes downstream to the distal edges of the landscape.

Chang et al. (2017) examined the velocity patterns and turbulent structures produced by a rigid, emergent circular patch, considering both flat and deformed bed conditions. According to their simulation results, the evolution of the bed from flat to equilibrium deformed conditions led to a reduction in the lengths of the steady wake and total wake regions. This finding aligns with the observations made by Kirkil et al. (2008, 2009) and Kirkil & Constantinescu (2010), who reported that the antisymmetric shedding mode was completely suppressed under equilibrium scour conditions. This suppression was attributed to the presence of upwelling flow near the symmetry plane at the rear of the cylinder (Figure 2.12). The upwelling flow, deflected by the water surface, pushes the separated shear layers away from both sides of the cylinder. Additionally, Aksel et al. (2021) observed that the presence of a scour hole and deposited mound signif-

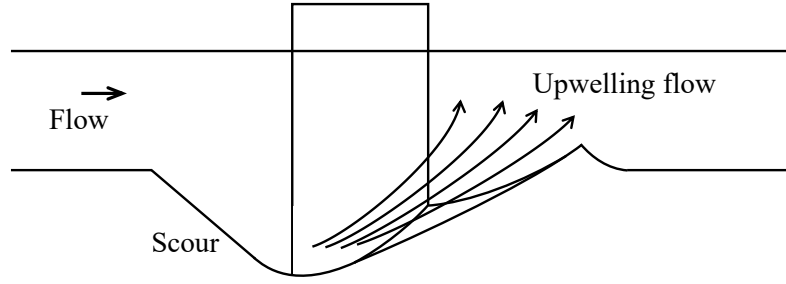


Figure 2.12: The upwelling flow at the back of the cylinder in deformed bed.

icantly weakened the lee-wake vortices behind the cylinder. Instead, a well-defined secondary flow structure, the large-scale counter-rotating streamwise vortices dominate the flow domain to a great extent in the wake. Similarly, Muzzammil & Gangadhariah (2003) and Narayana et al. (2022) found that the strength of vortices around a pier is decreased in mobile bed compared to rigid bed conditions. Waters & Crowe Curran (2016) found that the ripple formation inhibited the patch's wake structure, reducing the steady wake length.

The development of bedform alters the flow structure by modifying the flow resistance (Jumain et al. 2018). For example, Chang & Scotti (2003), Hurther & Thorne (2011), and Liang et al. (2025) reported that the development of ripples markedly increases near-bed turbulent kinetic energy by increasing the roughness height compared to a flat bed. Lefebvre et al. (2014) reported that the formation of dunes contributes to flow resistance by increasing drag exerted by the bed on the overlying flow. What's more, Artini et al. (2025a) found that, under comparable conditions, turbulent kinetic energy in mobile-bed scenarios was approximately two to three times greater than in fixed-bed cases, revealing the significant influence of dune geometry on turbulence. Furthermore, the turbulence level was higher with increasing dune size, particularly with dune height. However, the drag effects introduced by leafy vegetation and bedform were non-linear, highlight the interactions between foliage configuration and dune-related form drag (Artini et al. 2025b).

At the dune crest and on the lee-side of the dune, flow is separated, forming a separation zone behind the dunes (Dehsorkhi et al. 2011, Kwoil et al. 2016), affecting the mean flow around bedform by turbulent ejections of low momentum fluid over dune crests and recirculation cells (Best 2005). Meanwhile, a turbulent free shear layer emerges above the separation zone, which is enveloped by a turbulent wake (Kabiri et al. 2017). This shear layer is responsible for generating large-scale coherent structures that propagate throughout the flow domain and toward the water surface, gradually dissipating energy (Chang & Constantinescu 2013). Qiang et al. (2025) examined the influence of dune on very-large-scale motions in turbulent flow. Their results show that, for the low-angle dunes, the very-large-scale motions persist throughout the flow depth and are even intensified near the crest. In contrast, for the higher-angle dune, the intensity of the very-large-scale motions, quantified by turbulent kinetic energy and Reynolds stress, is

diminished within the near-bed separation zone, suggesting a local dominance of smaller-scale turbulent structures. This attenuation gradually decreases with increasing distance from the bed.

Ren et al. (2020) discovered that as bedform developed, bed elevation changed, leading to a flow readjustment (Dehsorkhi et al. 2011). As flow enters the eroded region, its velocity decreases, subsequently reducing the initiation of sediment transport. This may result in a dynamic equilibrium in the movement of sediment from the riffle to the pool, i.e., ripple migration, during the stable stage (Zhang, Cheng, Hassan, Wang & Wu 2024). In addition, the streamwise velocity in the mobile bed scenario was lower compared to the rigid bed condition, due to the energy consumed by sediment movement. Furthermore, Branß & Aberle (2022) found that conveyance capacity of the mobile bed channel was reduced compared to the fixed bed channel due to the additional roughness associated with bedform.

Dehsorkhi et al. (2013) observed a convex distribution of Reynolds stress both upstream and downstream of a bedform with vegetated banks. The convex Reynolds stress distribution on the upstream side of the bedform is attributed to a diffusion momentum defect, resulting from the wake of the upstream bedform overlaying a developing internal boundary layer (Fedele & García 2001). The Reynolds stress distribution over the bedform was dominated by turbulence generated within the free shear layer in the separation region downstream of the bedform crest. In addition, Mofrad et al. (2023) found that the Reynolds stress peaked closer to the bed when the submerged patch was in an artificial pool compared to that in a flat bed.

# Chapter 3

## Theory and experiment setup

This Chapter introduces the theory, materials and methods involved in the thesis, detailing both rigid-bed experiments to investigate flow–vegetation interactions and mobile-bed experiments to examine the interplay between flow, vegetation, and morphological changes.

### 3.1 Theory

#### 3.1.1 Governing equations

The present study focuses on patch-scale flow structures and their corresponding impacts. Each array is represented by circular cylinders with diameter,  $d$ , and the mean spacing between the centers of adjacent elements is denoted as  $\Delta S$ . The solid volume fraction,  $\Phi = N\pi d^2/4$ , quantifies the proportion of the patch volume occupied by solid elements, where  $N$  is the number of elements per unit area. The frontal area per unit volume is given by  $a = Nd$ . A double-averaging approach is employed to remove temporal and element-scale spatial heterogeneity (Rominger & Nepf 2011), leading to the following shallow water equations:

$$\frac{\partial h\langle\bar{u}\rangle}{\partial x} + \frac{\partial h\langle\bar{v}\rangle}{\partial y} = 0, \quad (3.1)$$

$$\frac{\partial h\langle\bar{u}\rangle\langle\bar{u}\rangle}{\partial x} + \frac{\partial h\langle\bar{u}\rangle\langle\bar{v}\rangle}{\partial y} = -\frac{1}{\rho} \frac{\partial h\langle\bar{p}\rangle}{\partial x} + \frac{1}{\rho} \left[ \frac{\partial h\langle\bar{\tau}_{xx}\rangle}{\partial x} + \frac{\partial h\langle\bar{\tau}_{xy}\rangle}{\partial y} \right] - hF_x \quad (3.2)$$

$$\frac{\partial h\langle\bar{u}\rangle\langle\bar{v}\rangle}{\partial x} + \frac{\partial h\langle\bar{v}\rangle\langle\bar{v}\rangle}{\partial y} = -\frac{1}{\rho} \frac{\partial h\langle\bar{p}\rangle}{\partial y} + \frac{1}{\rho} \left[ \frac{\partial h\langle\bar{\tau}_{yx}\rangle}{\partial x} + \frac{\partial h\langle\bar{\tau}_{yy}\rangle}{\partial y} \right] - hF_y \quad (3.3)$$

where  $u$  and  $v$  denote the fluid velocities in the  $x$  and  $y$  directions, respectively,  $h$  is the flow depth,  $\rho$  is the fluid density,  $p$  is the fluid pressure and  $\tau$  represents the shear stress.  $F_i$  is defined as the drag force exerted on the fluid in the  $i$ -th direction. The angled brackets represent

the spatial average and the overbar indicates the time average. Outside the vegetated region,

$$F_x = \frac{1}{2} \frac{C_f}{h} \langle \bar{u} \rangle (\langle \bar{u} \rangle^2 + \langle \bar{v} \rangle^2)^{1/2} \quad (3.4)$$

$$F_y = \frac{1}{2} \frac{C_f}{h} \langle \bar{v} \rangle (\langle \bar{u} \rangle^2 + \langle \bar{v} \rangle^2)^{1/2} \quad (3.5)$$

Inside the vegetated region,

$$F_x = \frac{1}{2} \frac{C_D a}{(1 - \Phi)} \langle \bar{u} \rangle (\langle \bar{u} \rangle^2 + \langle \bar{v} \rangle^2)^{1/2} \quad (3.6)$$

$$F_y = \frac{1}{2} \frac{C_D a}{(1 - \Phi)} \langle \bar{v} \rangle (\langle \bar{u} \rangle^2 + \langle \bar{v} \rangle^2)^{1/2} \quad (3.7)$$

where  $C_f$  is the bed friction coefficient and  $C_D$  is the drag coefficient of the plant elements. In the bare region, the solid volume fraction is zero,  $\Phi = 0$ . As the variations in water depth  $\Delta h$  were small, with values of  $\Delta h/h = O(10^{-3})$  for the scenarios considered in this thesis.  $h(x, y) = h$  was assumed to remain constant throughout the entire test section according to rigid-lid assumption. Inside the vegetated region, the bed drag is generally smaller than the vegetation drag, so the influence of the bed drag is ignored in Eq. 3.6 and Eq. 3.7. The drag force expressions given in Eq. 3.6 and Eq. 3.7 are valid only when the length scales considered are larger than the element spacing,  $\Delta S$ . In all scenarios considered in this thesis, however, the element spacing  $\Delta S$ , is much smaller than the overall dimensions of the vegetation patch. Therefore, the drag force defined here is appropriate for our analysis.

### 3.1.2 Velocity adjustment

Starting at the leading edge ( $x = 0$ ), velocity within the patch decelerated over the interior adjustment length,  $L_i$ , and then reached a nearly constant value. Within the interior adjustment region, Eq. 3.2 and Eq. 3.3 become

$$\langle \bar{u} \rangle \frac{\partial \langle \bar{u} \rangle}{\partial x} + \langle \bar{v} \rangle \frac{\partial \langle \bar{u} \rangle}{\partial y} = -\frac{1}{\rho} \frac{\partial \langle \bar{p} \rangle}{\partial x} - \frac{1}{2} \frac{C_D a}{(1 - \Phi)} \langle \bar{u} \rangle (\langle \bar{u} \rangle^2 + \langle \bar{v} \rangle^2)^{1/2} \quad (3.8)$$

$$\langle \bar{u} \rangle \frac{\partial \langle \bar{v} \rangle}{\partial x} + \langle \bar{v} \rangle \frac{\partial \langle \bar{v} \rangle}{\partial y} = -\frac{1}{\rho} \frac{\partial \langle \bar{p} \rangle}{\partial y} - \frac{1}{2} \frac{C_D a}{(1 - \Phi)} \langle \bar{v} \rangle (\langle \bar{u} \rangle^2 + \langle \bar{v} \rangle^2)^{1/2} \quad (3.9)$$

To determine  $L_i$ , the governing equations are scaled using the following characteristic values:

$$x \sim L_i \quad (3.10)$$

$$y \sim b \quad (3.11)$$

where  $b$  is half width of a in-flow located vegetation patch,

$$u \sim U_\infty \quad (3.12)$$

$$v \sim \frac{bU_\infty}{L_i} \text{ (Eq.3.1)} \quad (3.13)$$

$$\frac{\partial u}{\partial x} \sim \frac{\Delta u}{L_i} \quad (3.14)$$

$$\frac{\partial p}{\partial x} \sim \frac{\Delta p}{L_i} \quad (3.15)$$

The scaled governing equations become

$$\rho \frac{U_\infty^2}{L_i} \sim -\frac{\Delta p}{L_i} - \rho \frac{C_{Da}}{2(1-\Phi)} U_\infty^2 \left[ 1 + \left( \frac{b}{L_i} \right)^2 \right]^{1/2} \quad (3.16)$$

$$\rho \frac{U_\infty^2 b}{L_i} \sim -\frac{\Delta p}{b} - \rho \frac{C_{Da}}{2(1-\Phi)} U_\infty^2 \left[ \left( \frac{b}{L_i} \right)^2 + \left( \frac{b}{L_i} \right)^4 \right]^{1/2} \quad (3.17)$$

Dividing by the inertial term in each equation, respectively, the equations are simplified to

$$1 \sim -\frac{\Delta p}{\rho U_\infty^2} - \frac{1}{2(1-\Phi)} \left[ (C_{Da}L_i)^2 + (C_{Dab})^2 \right]^{1/2} \quad (3.18)$$

$$1 \sim -\frac{L_i^2 \Delta p}{b^2 \rho U_\infty^2} - \frac{1}{2(1-\Phi)} \left[ (C_{Da}L_i)^2 + (C_{Dab})^2 \right]^{1/2} \quad (3.19)$$

Here,  $C_{Dab}$  denotes the non-dimensional flow-blockage of the array. Patches with higher  $C_{Dab}$  values are classified as high flow-blockage patches, whereas those with lower  $C_{Dab}$  values are considered low flow-blockage patches. For high flow-blockage patches, the pressure rise at the leading edge is on the order of  $\Delta p \sim \rho U_\infty^2$  whereas for low flow-blockage patches,  $\Delta p$  approaches 0. For the low flow-blockage patch, with  $\Delta p \approx 0$  and  $\Phi \ll 1$ . Eq. 3.18 and Eq. 3.19 give,

$$L_i \sim \frac{2}{C_{Da}}. \quad (3.20)$$

To address the minor yet non-negligible pressure change at the leading edge of low flow-blockage patches, a correction term is incorporated. For sparse patches with  $ab < 0.1$ , Belcher et al. (2003) observed that  $\Delta p / \rho U_\infty^2 \sim (C_{Dab})^2$ . Therefore, for low flow-blockage patches,

$$L_i \sim \frac{2}{C_{Da}} (1 + (C_{Dab})^2). \quad (3.21)$$

For high flow blockage patches,  $\Delta p \sim \rho U_\infty^2$ . The pressure term must be  $O(1)$  in both equations, leading to

$$L_i \sim b. \quad (3.22)$$

The scaling for  $\Delta p \sim \rho U_\infty^2$  is valid for  $C_{Dab} > 2$ . For values of  $C_{Dab} < 2$ ,  $\Delta p / \rho U_\infty^2$  increases with  $C_{Dab}$  and  $\Delta p$  approaches zero as  $C_{Dab}$  approaches zero. Therefore, a threshold value of 2 is used to distinguish between high and low flow-blockage patches. Finally, by fitting the experimental data, the interior adjustment length over a flat bed predict (Rominger & Nepf 2011)

$$L_i = \begin{cases} (3.0 \pm 0.3) \left[ \frac{2}{C_{Da}} (1 + (C_{Dab})^2) \right], & C_{Dab} < 2 \\ (7.0 \pm 0.4)b, & C_{Dab} \geq 2. \end{cases} \quad (3.23)$$

### 3.1.3 Shear layer penetration

Two distinct length scales characterize the shear flow across the interface of a vegetation patch, the inner penetration thickness within the vegetated region ( $\delta_I$ ) and the outer penetration thickness outside the vegetated region ( $\delta_O$ ). If the shear layer is independent of the channel wall and array dimensions, the penetration scale inside the array can be obtained by scaling the momentum equation in the sharp transition zone at the interface, where the interfacial shear stress is nearly balanced by hydraulic resistance.

Analogous to boundary-layer flows, a friction velocity can be defined as the maximum shear stress at the interface,

$$u_*^2 = -\tau_{xy}/\rho = \max(-\langle u'v' \rangle), \quad (3.24)$$

which occurs very close to the interface of the array. According to the balance between shear stress and drag forces within the inner penetration region, we have

$$\frac{u_*^2}{\delta_I} \sim \frac{1}{2} \frac{C_{Da}}{(1-\Phi)} U_I^2, \quad (3.25)$$

in which  $U_I$  is the velocity at the interface of the array. Thus,

$$\delta_I \sim (C_{Da})^{-1}. \quad (3.26)$$

For scenarios with significant patch drag ( $C_{Da}$ ), where the shear layer cannot penetrate over the first row of cylinders, the cylinder diameter defines a lower bound for  $\delta_I$ . Previous experimental data (White & Nepf 2008) reported that  $\delta_I \approx 1.8d$  in this high-density scenario. Accordingly, the inner penetration thickness is defined as,

$$\delta_I \approx \max[0.5(C_{Da}), 1.8d]. \quad (3.27)$$



Inside the vegetated areas, the flow outside the shear layer is laterally uniform, and the spatially and temporally averaged velocity is denoted as  $U_1$ . Then, Eq. 3.2 can be simplified to

$$0 = -\frac{1}{\rho} \frac{\partial \langle \bar{p} \rangle}{\partial x} - \frac{1}{2} \frac{C_D a}{(1 - \Phi)} U_1^2. \quad (3.28)$$

Here, the pressure gradient arises from the free surface slope,

$$g \frac{\partial h}{\partial x} = \frac{1}{\rho} \frac{\partial \langle \bar{p} \rangle}{\partial x}. \quad (3.29)$$

Then,

$$\frac{1}{2} \frac{C_D a}{(1 - \Phi)} U_1^2 = -g \frac{dh}{dx} \quad (3.30)$$

and

$$U_1 = \sqrt{-\frac{2g(1 - \Phi)}{C_D a} \frac{dh}{dx}}. \quad (3.31)$$

Within the outer penetration region, the pressure gradient resulting from the free-surface slope approximately balances the shear stress,

$$\frac{u_*^2}{\delta_O} \sim g \frac{dh}{dx}. \quad (3.32)$$

For the uniform flow in the main channel outside the shear layer ( $U_2$ ), we have

$$g \frac{dh}{dx} = -\frac{1}{2} \frac{C_f}{h} U_2^2 \quad (3.33)$$

and

$$U_2 = \sqrt{\frac{2gh}{C_f} \frac{dh}{dx}}. \quad (3.34)$$

Considering Eq. 3.32 and Eq. 3.33, we have

$$\frac{u_*^2}{\delta_O} \sim \frac{1}{2} \frac{C_f}{h} U_2^2 \quad (3.35)$$

and the outer penetration length scale become

$$\delta_O \sim \frac{u_*^2}{U_2^2} \frac{2h}{C_f}. \quad (3.36)$$

### 3.1.4 Vortex frequency

The Kelvin-Helmholtz (KH) vortices within a shear layer have a frequency (Ho & Huerre 1984),

$$f_{KH} = \frac{0.032\bar{U}}{2\theta} \quad (3.37)$$

in which  $\bar{U} = 1/2(U_1 + U_2)$  and

$$\theta = \int_{-\infty}^{\infty} \left[ \frac{1}{4} - \left( \frac{\bar{u}(y) - \bar{U}}{\Delta U} \right)^2 \right] dy \quad (3.38)$$

$U_1$  and  $U_2$  are the lowest velocity within the array and highest velocity adjacent to the array, respectively, and  $\Delta U = U_2 - U_1$ . This frequency has been widely used to predict the KH vortex shedding frequency in vegetated channels with emergent cylinders (White & Nepf 2008), as well as in submerged canopies composed of both rigid and flexible plants (Ghisalberti & Nepf 2002).

Based on extensive literature on the wakes of cylinders with diameter  $D$ , the Strouhal number is given by  $St = fD/U \approx 0.2$  for Reynolds numbers in the range  $200 < Re < 3 \times 10^5$  (Roshko 1961, Schewe 1983). Zong & Nepf (2012) confirmed that the von Karman vortex street formed behind a porous patch of cylinders exhibits a frequency

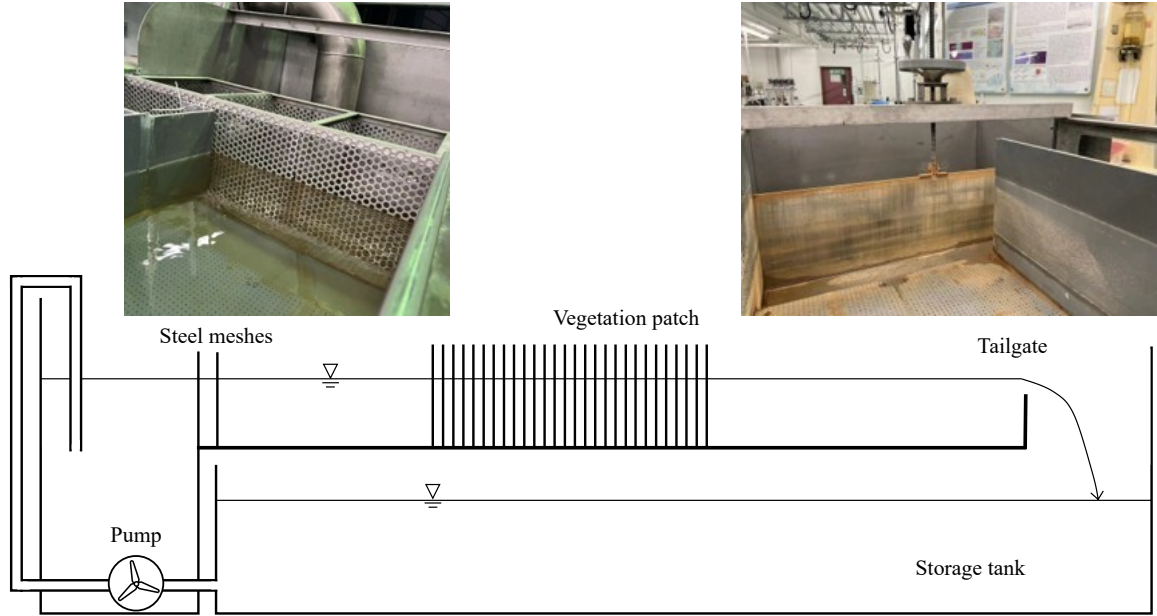
$$f_{VK} = \frac{0.2U_2}{D}. \quad (3.39)$$

## 3.2 Rigid-bed experiments

To investigate the flow structure in vegetated flows, laboratory experiments were carried out in a recirculating flume with rigid bed which was fully covered by polyvinyl chloride (PVC) board. The flume has a slope of  $S_b = 1/1000$ . The test section has a width ( $B$ ) of 0.6 m and a length of 7 m. At the upstream inlet of the flume, two steel mesh screens were fixed to minimize water-surface oscillations (Figure 3.1a). A tailgate was installed at the downstream end of the test section to control the water level (Figure 3.1b).

To obtain a sub-critical and turbulent incoming flow, the water level was controlled to be  $h = 22.0 \pm 0.2$  cm, measured with a point gauge upstream of the vegetated region, where the flow was unaffected by the presence of vegetation. The incoming flow was laterally uniform (Figure 3.2a), with a mean velocity of  $U_\infty = 8.0 \pm 0.1$  cm/s. The channel Froude number ( $Fr = U_\infty/(gh)^{1/2}$ ) and the channel Reynolds number ( $Re = U_\infty h/\nu$ , where  $\nu$  is the kinematic viscosity of the water,  $\nu = 10^{-6} \text{m}^2/\text{s}$ ) were 0.05 and 17,600, respectively (Table 3.1).

(a)



(b)

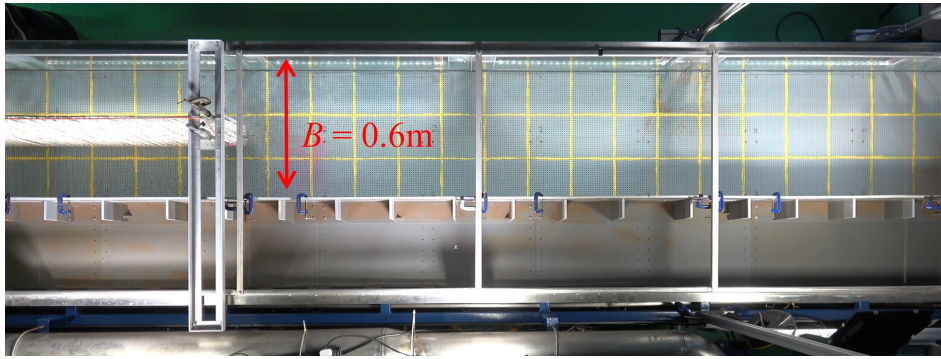


Figure 3.1: (a) The mesh screens at the upstream inlet of the flume and the tailgate at the downstream end of the channel. (b) The top view of the rigid-bed flume.

|                 | $U_{\infty}$ (m/s) | $h$ (m/s) | $Fr$ | $Re$   |
|-----------------|--------------------|-----------|------|--------|
| Rigid-bed test  | 0.08               | 0.22      | 0.05 | 17,600 |
| Mobile-bed test | 0.15               | 0.2       | 0.11 | 32,000 |

Table 3.1: Summary of hydraulic conditions.  $U_{\infty}$  is the mean upstream velocity.  $h$  is the water depth. For mobile-bed test,  $h$  is the water depth above the top of the initially flat sand layer.  $Fr = U_{\infty}/(gh)^{1/2}$  is the channel Froude number and  $Re = U_{\infty}h/\nu$  is the channel Reynolds number.

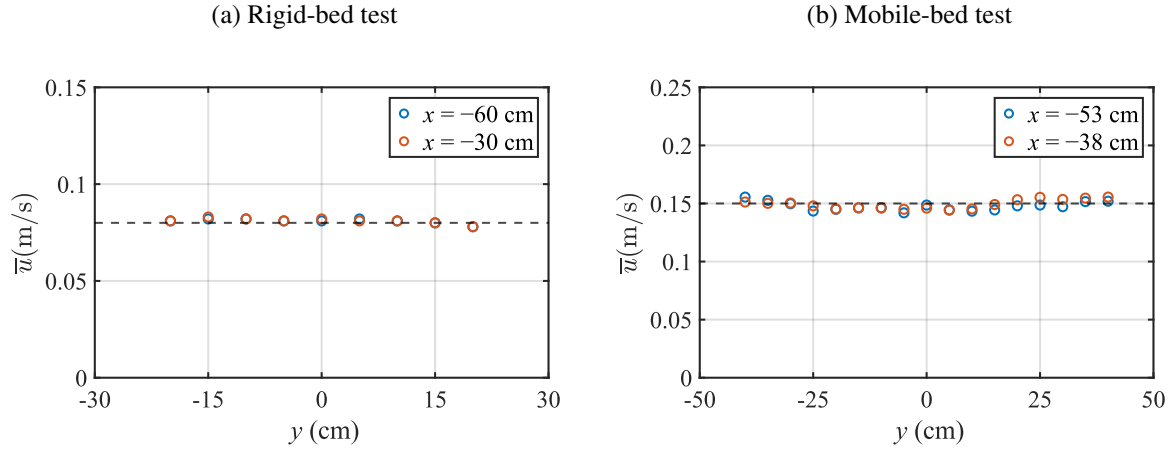


Figure 3.2: The lateral distribution of time-averaged streamwise velocity ( $\bar{u}$ ) measured upstream of the patch confirmed the laterally uniform conditions.  $x = 0$  is the leading edge of the patch.  $y = 0$  is the centerline of the patch and channel. The dashed line indicates the mean upstream velocity,  $U_\infty$ .

### 3.3 Mobile-bed experiments

To correlate the flow structure with the bed morphology development, mobile-bed experiments were conducted by placing a sand layer on the flume bottom. These experiments were conducted in a 1-m-wide and 10.4-m-long horizontal channel, with water and sediment recirculated separately (Figure 3.3). Sediment was collected at the end of the test section and recirculated to a sediment return. The sediment return positioned above the flume, which enabled laterally uniform sediment release. An array of dowels was installed below the sediment return to dissipate the energy from the falling water and to smooth the incoming flow.

To highlight the influences of flow structure on bedform development without considering the armoring effects introduced by sediment heterogeneity, an 8-cm layer of uniform sand ( $d_{50} = 0.35$  mm,  $\rho_s = 2,650$  kg/m<sup>3</sup>) was placed over the entire 10.4 m test section and manually flattened. The water depth was  $h = 20$  cm above the top of the initially flat sand layer, measured with a ruler upstream of the array. The mean water surface had negligible (less than 5 mm) variation along the flume length. The incoming (and channel average) velocity was  $U_o = 16.0 \pm 0.8$  cm/s. The channel Froude and Reynolds numbers were  $Fr = U_o / \sqrt{gh} = 0.11$  and  $Re = U_o h / \nu = 32,000$ , respectively (Table 3.1). The Froude and Reynolds numbers indicated that the flow was subcritical and fully turbulent. The bed friction coefficient  $C_f$  represented both grain resistance and the bedform drag, when present

$$C_f = \frac{1}{8} \left( 0.32 \left( \frac{d_{50}}{h} \right)^{1/3} + \frac{\Delta}{\Lambda} \right) \quad (3.40)$$

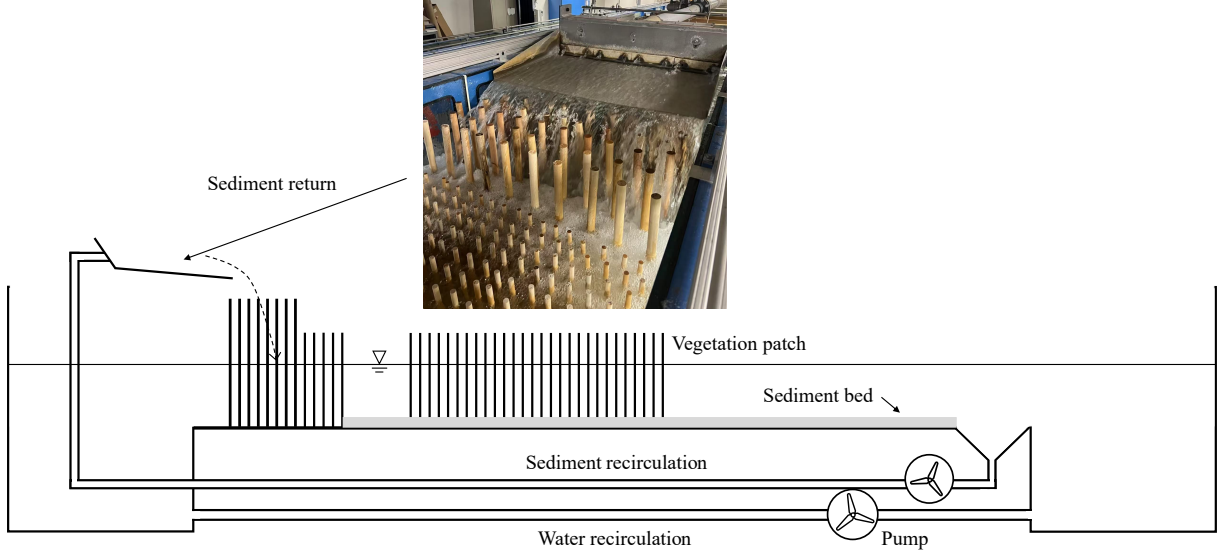


Figure 3.3: Sediment return and dowels installed upstream of the test section. The tall dowels are used to dissipate the energy caused by the water drop. The short dowels are used to smooth the incoming flow.

in which  $\Delta$  is the dune height, and  $\Lambda$  is the dune length (Eq. 8.18b and 8.21 in Julien (2010)). For the initial flat bed,  $C_f = \frac{1}{8} \left( 0.32 \left( \frac{d_{50}}{h} \right)^{\frac{1}{3}} \right) = 0.005$ . The dimensionless particle diameter  $d_* = d_{50} \left[ \frac{(\rho_s - \rho)g}{\rho v^2} \right]^{1/3} = 8.85$ . For  $0.3 < d_* < 19$ , the critical Shields parameter  $\tau_{*c} = 0.25d_*^{-0.6} \tan 30^\circ = 0.039$  (Julien 2010), indicating a critical shear velocity of  $u_{*c} = \sqrt{\frac{(\rho_s - \rho)g}{\rho} d_{50} \tau_{*c}} = 0.015 \text{ m/s}$ . The incoming velocity was lower than the critical velocity required for the sediment motion,  $U_o = 0.15 \text{ m/s} < U_c = u_{*c} / \sqrt{C_f} = 0.22 \text{ m/s}$ . Consistent with this calculation, no sediment motion was observed in the region upstream of the array, and the bed surface remained flat after exposure to water flow (Figure 3.4). The critical bed shear stress  $\tau_c = \tau_{*c}(\rho_s - \rho)gd_{50} = 0.22 \text{ Pa}$ , was used to infer a critical level of turbulent kinetic energy for sediment motion,  $k_{t,c} = \tau_c / 0.19\rho = 1.2 \times 10^{-3} \text{ m}^2/\text{s}^2$  (e.g., Yang et al. (2016)).

### 3.4 Vegetation patch

The present work did not consider the influence of plant morphology, complex natural aquatic plant was represented by simplified geometric analogs. Here, vegetation patches were modeled with circular rigid rods that extended from the bottom through the water surface, i.e., emergent. The patches were placed at the position where the streamwise velocity was laterally uniform (Figure 3.2). By controlling the stem space and stem diameter  $d$ , the number of rods per unit bed area  $N(\text{m}^{-2})$ , the frontal area per unit volume  $a = Nd(\text{m}^{-1})$  and the average solid volume fraction  $\Phi = Nd^2/4$ , could be obtained accordingly, all of which described the fundamental



Figure 3.4: Bedform observed upstream of the vegetation array. In this region, the velocity was not affected by the presence of vegetation patch, suggesting that the incoming velocity was below the critical threshold necessary to initiate sediment movement, thereby maintaining a flat bed.

resistance properties of the patches. This study did not consider the variation caused by the stem arrangement within the patch. To ensure sufficient space for velocity measurements within the patch and avoid the disturbance caused by the stems, individual rods were held in an aligned pattern by perforated PVC baseboards extended over the entire test section bottom. In mobile-bed experiments (Chapter 7), the perforated PVC baseboards were placed below the sand layer.

For rigid-bed experiments (Chapter 4, 5, 6), vegetation patches were modeled with circular PVC rods of a diameter  $d = 3.2$  mm, which was chosen to fall in the range of observed values for emergent plants,  $d = 1 \sim 10$  mm (Valiela et al. 1978, Leonard & Luther 1995, Lightbody & Nepf 2006). For mobile-bed experiment (Chapter 7), the model vegetation consisted of circular wooden dowels with a diameter  $d = 1.27$  cm.

### 3.5 Flow and bedform measurement

Velocity measurements were obtained using a 3D down-looking acoustic Doppler velocimeter (ADV) with a sampling duration of 120 s. The adequacy of this sampling period was verified through a convergence test of mean and turbulent flow statistics (Figure 3.5). To enhance the backscatter signal, spherical glass beads (Potters Industries Inc. 110P8, median grain size  $d_{50} = 10\mu\text{m}$ ) were added to the flow. Two types of ADV were employed: the Nortek Vectrino Profiler for rigid-bed experiments and the Nortek Vectrino Plus for mobile-bed experiments. The Nortek Vectrino Profiler can collect velocities within  $40 \sim 72$  mm below the probe, with user-defined cell sizes ranging from  $1 \sim 4$  mm. For the rigid-bed experiments (Chapter 4, 5, 6), only 11 cells with a 2 mm cell size (total measurement length = 20 mm) were selected to ensure sampling data quality, corresponding to a measurement range of  $40 \sim 60$  mm from the probe. The Nortek

Vectrino Plus can collect velocity 5 cm from the down-looking probe, with a sampling volume of 6 mm in diameter and 3 mm in height. Details of data collection and ADV configuration are summarized in Table 3.2.

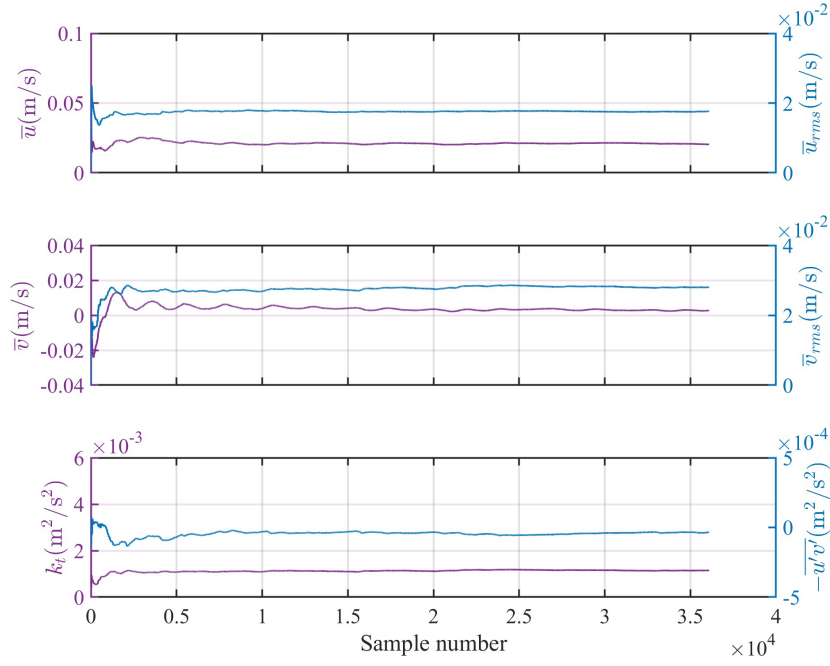
|                             | Rigid-bed test             | Mobile-bed test            |
|-----------------------------|----------------------------|----------------------------|
| Velocity measurement        | Nortek Vectrino Profiler   | Nortek Vectrino Plus       |
| Sampling frequency          | 75 Hz                      | 200 Hz                     |
| Collection time             | 120 s                      | 120 s                      |
| Probe                       | down-looking               | down-looking               |
| Collection position         | 40-60 mm<br>from the probe | 50-57 mm<br>from the probe |
| Sampling volume<br>diameter | 7 mm                       | 6 mm                       |
| Cell size                   | 2 mm                       | 7 mm                       |
| Cell number                 | 11                         | 1                          |

Table 3.2: Summary of data collection and ADV configuration.

For each sampling point within the array, the ADV was placed as close as possible to the midpoint between four dowels. The velocity at this position was confirmed to be within 11% of the spatially averaged velocity measured by five positions within a unit cell, including four corners and one center point (see Figure 3.6). For experiments carried out on a mobile bed, velocity measurements were made at several times after the start of the experiment to observe how the evolution of the bedform influenced the velocity field. Once the velocity became steady with time, we considered the bedform to be fully developed, though some minor ripple migration continued to be observed. The bed elevation was measured with a vertical resolution of  $\pm 1$  mm before and after exposure to a fixed duration of flow using a down-looking ADV. The change in bed elevation before and after exposure to flow is defined as the net deposition  $\delta_b$ .

Within the vegetation patch, flow is governed by a balance between vegetation-induced drag and the hydraulic gradient. As the stem density is vertically uniform, the drag force is distributed evenly from the bed to the water surface. Additionally, the hydraulic gradient remains constant over the entire water depth. As a result, the vertical profile of streamwise velocity within the emergent vegetation patch is uniform distributed. Furthermore, stem-scale turbulence generated within the patch reduces the thickness of the bottom boundary layer, which further contributes to flattening of the velocity profile. Based on vertical profiles measured in the current experiments (Figure 3.7) and previous studies for emergent arrays of cylinders (Shan et al. 2020, Zhao & Nepf 2021), the velocity measured at mid-depth can reasonably represent the depth-averaged velocity, and the flow can be considered approximately two-dimensional. The origin of the Cartesian coordinate system ( $x = 0$ ,  $y = 0$ ) was placed at the leading edge of the array and

(a) Rigid-bed test



(b) mobile-bed test

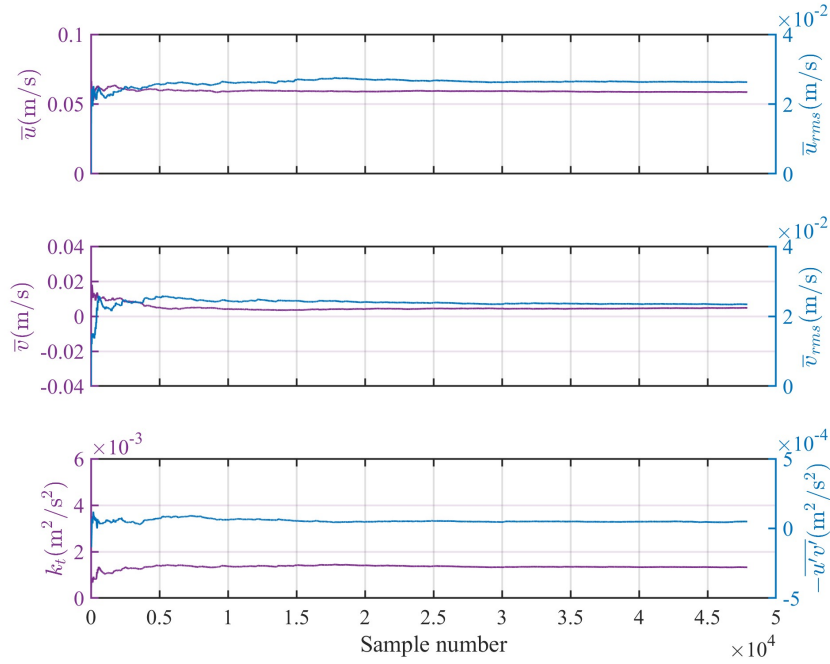


Figure 3.5: Convergence test confirmed that the 120 s sampling duration was sufficient. Here, cumulatively averaged velocity ( $\bar{u}$  and  $\bar{v}$ ), root-mean-square of the fluctuating velocity ( $u_{rms}$  and  $v_{rms}$ ), turbulent kinetic energy ( $k_t$ ), horizontal shear stress ( $-\overline{u'v'}$ ) are plotted against accumulated sample number. The sampling frequency was (a) 75 Hz in rigid-bed test, (b) 200 Hz in mobile-bed test. All averages converged within 20000 sample points.



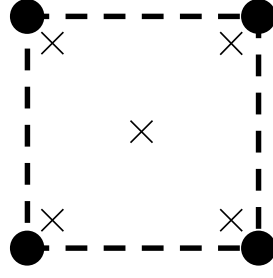


Figure 3.6: A unit cell. The velocity measured at the midpoint between four dowels (denoted by black circle) was within 11% of the spatially averaged velocity measured by five positions within the unit cell, including four corners and one center point (denoted by ‘x’).

at the mid-point of the channel, respectively, with  $x$  positive in the streamwise direction. The velocity components were denoted as  $(u, v)$  in the  $(x, y)$  directions, respectively. The flow structure and morphological changes were mostly symmetric across the centerline of the array and channel, which was confirmed by the measurements across the whole flume width (Figure 3.8). Subsequently, to reduce measurement time, the lateral transects were collected over half of the flume width.

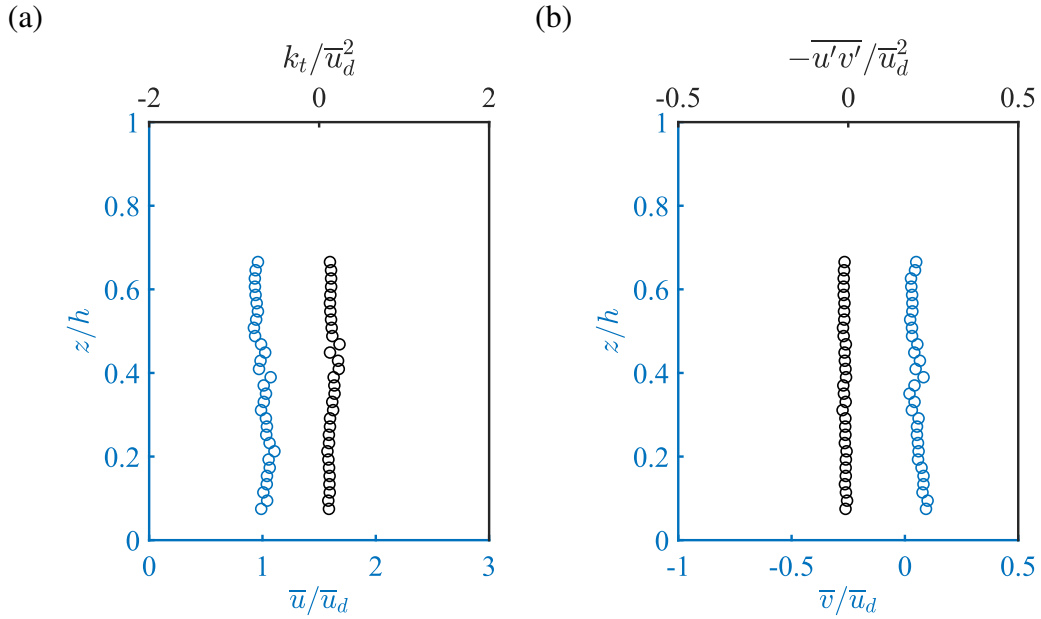


Figure 3.7: Vertical profiles of time-averaged (a) streamwise velocity ( $\bar{u}$ ) and turbulent kinetic energy ( $k_t$ ), and (b) transverse velocity ( $\bar{v}$ ) and Reynolds shear stress ( $-\overline{u'v'}$ ).  $\bar{u}_d$  is the depth-averaged streamwise velocity. Because the profiles are vertically uniform, the time-mean and turbulent velocity characteristics collected at mid-depth can reasonably represent the depth-average, and the flow can be considered approximately two-dimensional.

Measurements of two-dimensional time-dependent velocity fields on the water surface were

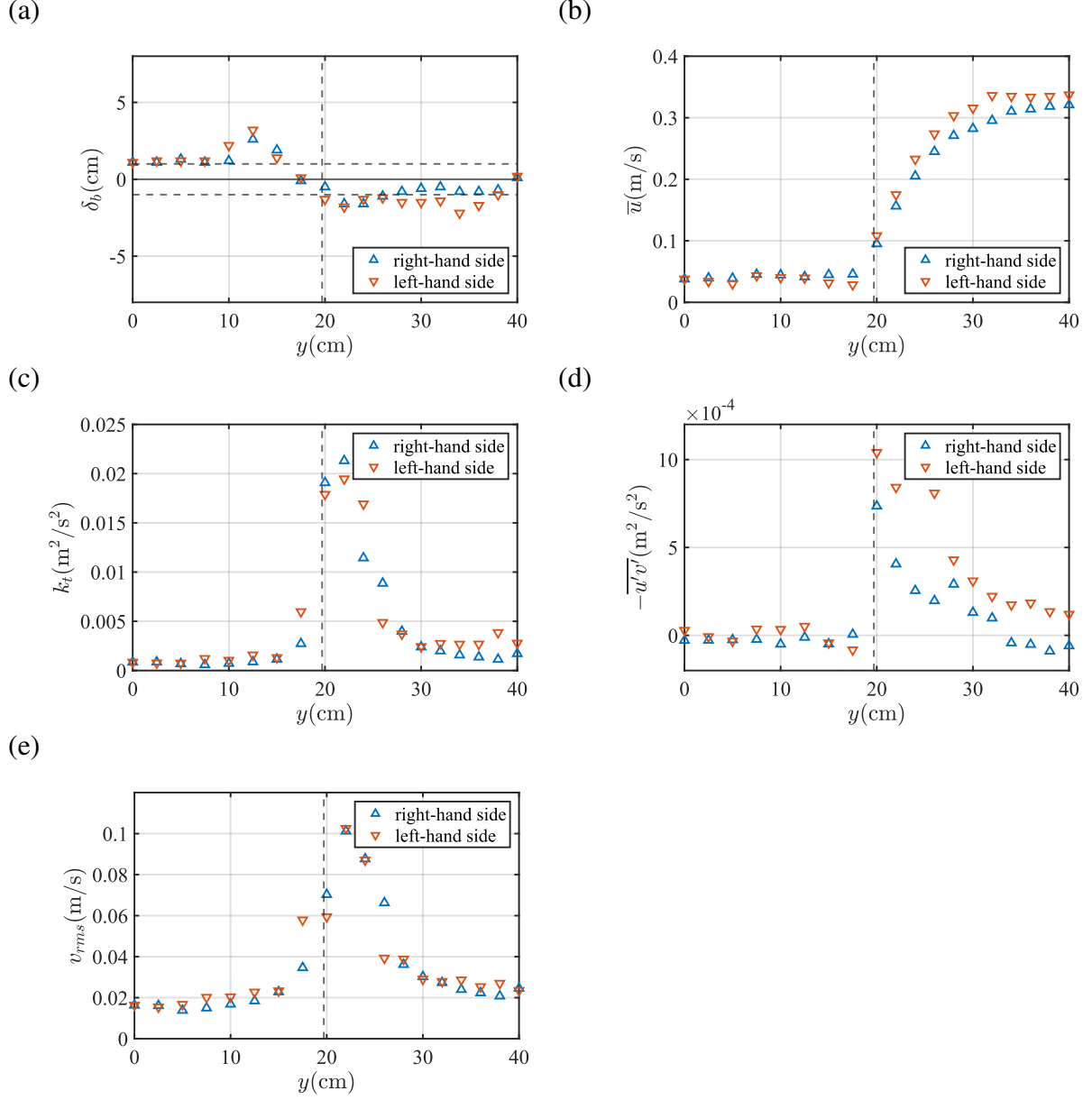


Figure 3.8: Lateral profiles for (a) bed elevation ( $\delta_b$ ), (b) time-averaged streamwise velocity ( $\bar{u}$ ), (c) turbulent kinetic energy ( $k_t$ ), (d) horizontal shear stress ( $-\overline{u'v'}$ ) and (e) the root-mean-square of the fluctuating spanwise velocity ( $v_{rms}$ ). The dashed line indicates the lateral interface of the patch. The flow structure and morphological changes were mostly symmetric across the centerline of the array and channel ( $y = 0$ ).

carried out by means of a two-dimensional Particle Image Velocimetry (PIV) analysis. By recording images with cameras, the relative displacement of seed particles within a flow can be determined. Once corrected for time and space, an instantaneous vector field can be produced. In this experiment, four high-speed cameras were used. They were fixed on rigid supports at an elevation of around 5 m from the bottom of the channel, pointing downwards. Each camera recorded 4000 frames for each acquisition, with an acquisition frequency of 100 Hz. The resolution of each camera is  $1920 \times 1080$  pixels. The illumination has been provided by five white LEDs of 1000 W each. White plastic particles with a mean diameter of  $550 \mu\text{m}$  and a density of about  $1.05 \text{ g/cm}^3$  were used as tracers for the PIV. The bottom and side wall of the flume and the surface of model vegetation were painted black.

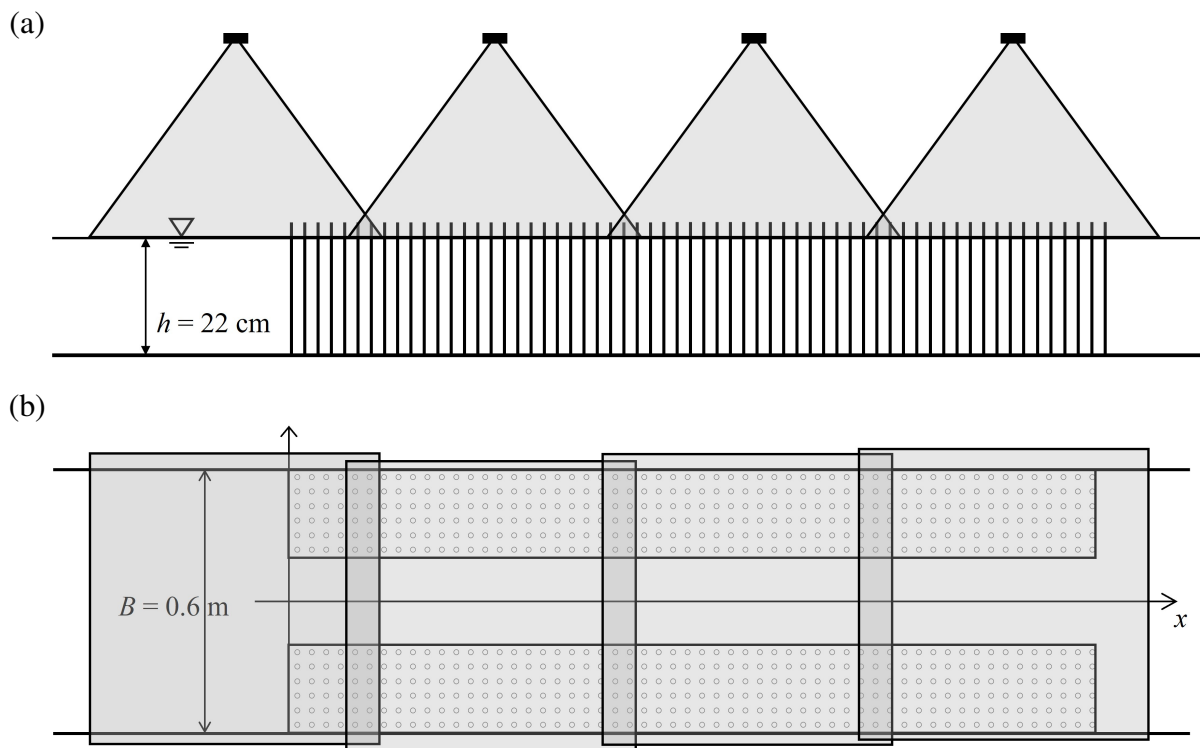


Figure 3.9: The experimental setup for Particle Image Velocimetry (PIV) analysis from (a) side view and (b) top view.

The images from the four digital cameras overlapped by approximately 20% in the stream-wise direction. Then, the images from the four cameras were processed in order to obtain a single panoramic image of the entire region of interest (Figure 3.10). The spatial resolution obtained was  $x = -0.5 \sim 4.4\text{m}$  and  $y = -0.3 \sim 0.3\text{m}$ , leading to vector velocity fields evaluated on a grid  $256 \times 91$ . Spatial calibration is always required when adopting a PIV technology. Several calibration targets were used, which was placed at the height corresponding to the water surface. Each calibration target measures an area of  $0.5\text{m}$  by  $0.5\text{m}$  and features a staggered black-and-white grid with individual squares measuring  $0.05 \text{ m}$  by  $0.05\text{m}$ . To cover the  $0.6\text{m}$ -wide flume,

the calibration targets were placed sequentially at either side along the width (Figure 3.10a).

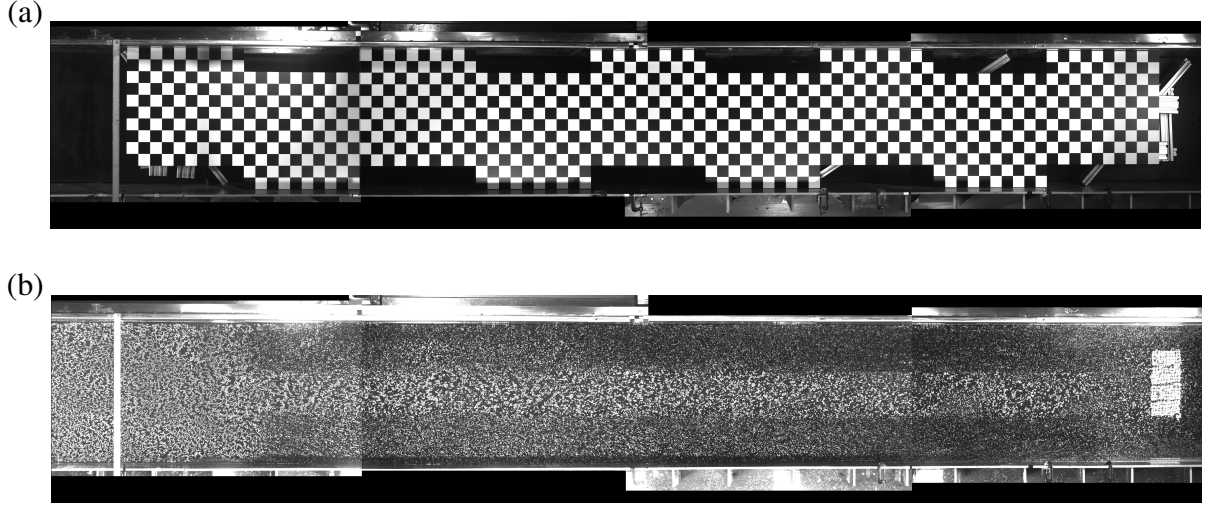


Figure 3.10: Panoramic view after merging process of the four camera acquisitions: during (a) calibration, (b) image acquisitions, in which the darker regions indicate the vegetated arrays with less particles.

Figure 3.11 shows the time-averaged streamwise velocity ( $\bar{u}$ ) profiles measured at mid-depth using ADV and at the water surface using PIV. For all scenarios considered, the root-mean-square deviation between the two measurement methods was less than 2%. Figure 3.13 demonstrates that the vortex frequencies measured at mid-water depth using ADV closely match those obtained at the water surface with PIV, within uncertainty. The agreement between the mid-depth and water surface measurements suggests that the flow structure within and around emergent vegetation patches can be considered two-dimensional.

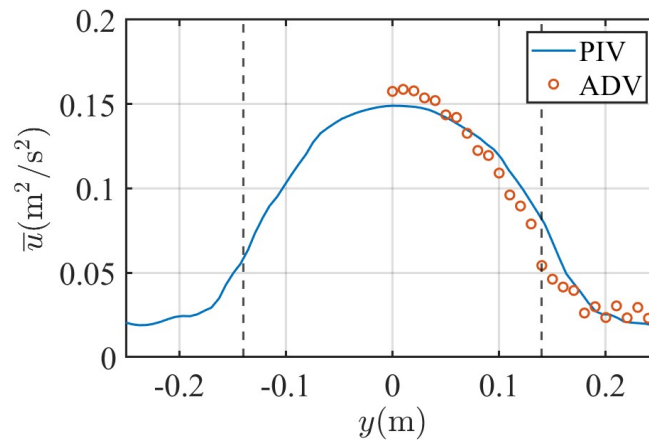


Figure 3.11: Comparison of lateral profiles of time-averaged streamwise velocity ( $\bar{u}$ ) in the fully developed region, measured at the middle of water depth using ADV and at the water surface using PIV. The dashed lines indicate the interfaces of the vegetation arrays.

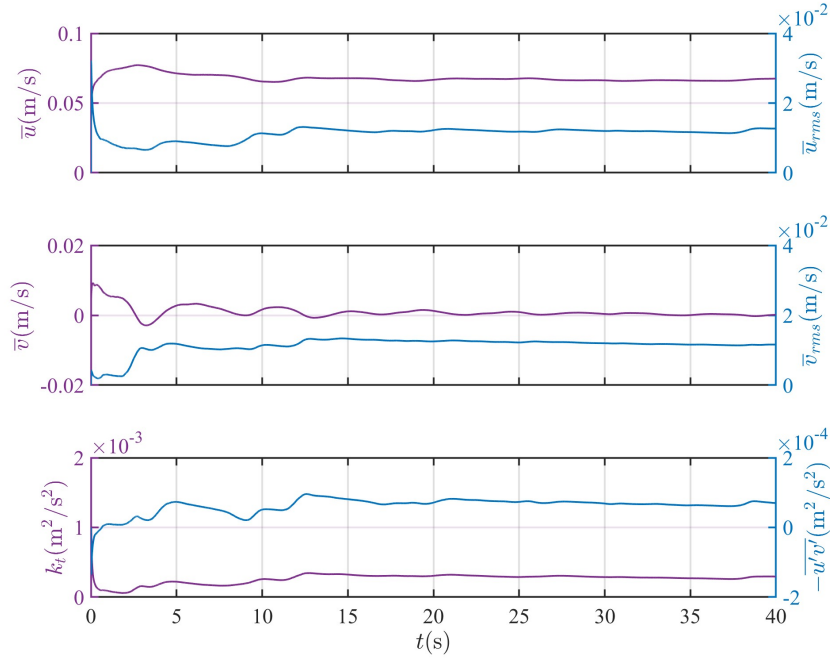


Figure 3.12: Convergence test for PIV analysis confirmed that the 40 s sampling duration was sufficient. Here, cumulatively averaged velocity ( $\bar{u}$  and  $\bar{v}$ ), root-mean-square of the fluctuating velocity ( $u_{rms}$  and  $v_{rms}$ ), turbulent kinetic energy ( $k_t$ ), horizontal shear stress ( $-\overline{u'v'}$ ) are plotted against accumulated sampling time. The sampling frequency was 100 Hz.

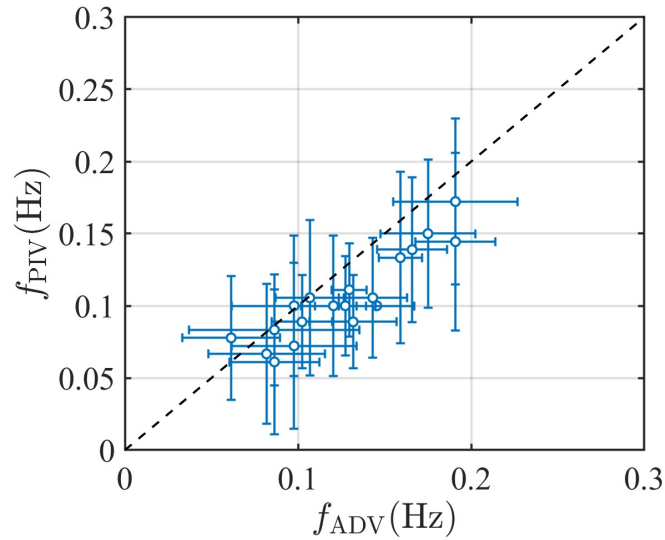


Figure 3.13: Comparison of vortex frequencies collected at the middle of water depth by ADV and on the water surface by PIV. The dashed line is a 1:1 ratio.

### 3.6 Data treatment

The raw velocity data was prefiltered by removing data with a correlation coefficient less than 70%. The spikes in velocity records were removed by the method developed by Goring & Nikora (2002). The velocity time series before and after denoising are shown in Figure 3.14. Each velocity record was decomposed into time-averaged ( $\bar{u}$ ,  $\bar{v}$ ) and fluctuating ( $u'$ ,  $v'$ ) components. The initiation and evolution of turbulent structures were evaluated using the power spectral density ( $S_{vv}$ ) and autocorrelation function ( $R_{vv}$ ) of the cross-stream velocity ( $v$ ), time-averaged Reynolds stress,  $-\overline{u'v'}$ , turbulent kinetic energy  $k_t = 1/2(\overline{u'^2} + \overline{v'^2})$ , and root-mean-square velocity fluctuation,  $u_{rms} = \sqrt{\overline{u'^2}}$ ,  $v_{rms} = \sqrt{\overline{v'^2}}$ . The PSD was estimated by Welch's method (Welch 1967), as described in the MATLAB toolbox. Peaks in the PSD indicated the presence of coherent vortices and their dominant frequency. The lateral profiles of velocity were used to estimate the momentum thickness of the shear-layer ( $\theta$  in Eq. 3.38) and the expected dimensionless frequency of the Kelvin-Helmholtz instability,  $f_{KH}\theta/\bar{U} = 0.032$  (Eq. 3.37), in which  $\bar{U} = 1/2(U_1 + U_2)$ .  $U_1$  and  $U_2$  are the lowest velocity within the array and highest velocity adjacent to the array, respectively. The von Karman vortex formed in the wake of the array was expected to have a frequency  $f_{VK}$  in agreement with Strouhal number  $2f_{VK}b/U_2 = 0.2$  (Eq. 3.39), based on a previous study of porous cylinder wakes (Zong & Nepf 2012).

### 3.7 Dye visualization

Flow visualization was used to examine the vortex structures, by injecting dye with a constant flow rate. A camera was placed above the region of interest to capture the flow structure. Videos were recorded over 1 min for all cases, starting at the beginning of the dye injection. Considering the shedding period of a von Karman vortex and Kelvin-Helmholtz vortex from previous studies and our observations, the recording duration was enough to cover several vortex formations. Pictures were post-processed using Photoshop software to enhance the color of the dye. For experiment carried out on a rigid bed, yellow colored grid lines at the bottom were used to provide a distance reference (Figure 3.15). To observe the mixing and interaction of the shear-layer vortices, red and green dyes were released on either side of the patch. To illuminate the observed region and minimize light reflections from the water surface, several light-emitting diodes (LEDs) were installed along the glass flume wall when the vegetation patch was centrally located. When the patch was positioned along the sidewall, the LEDs were arranged above the flume. A high-resolution camera (Sony FDR-AXP55,  $3480 \times 2160$  pixels) was used, recording videos with 25 frames per second. For experiments carried out on a mobile bed, dye visualization was conducted at different running times to evaluate the impact of the deformed bed on the vortex structures. A GoPro camera ( $2704 \times 2028$  pixels) was used,

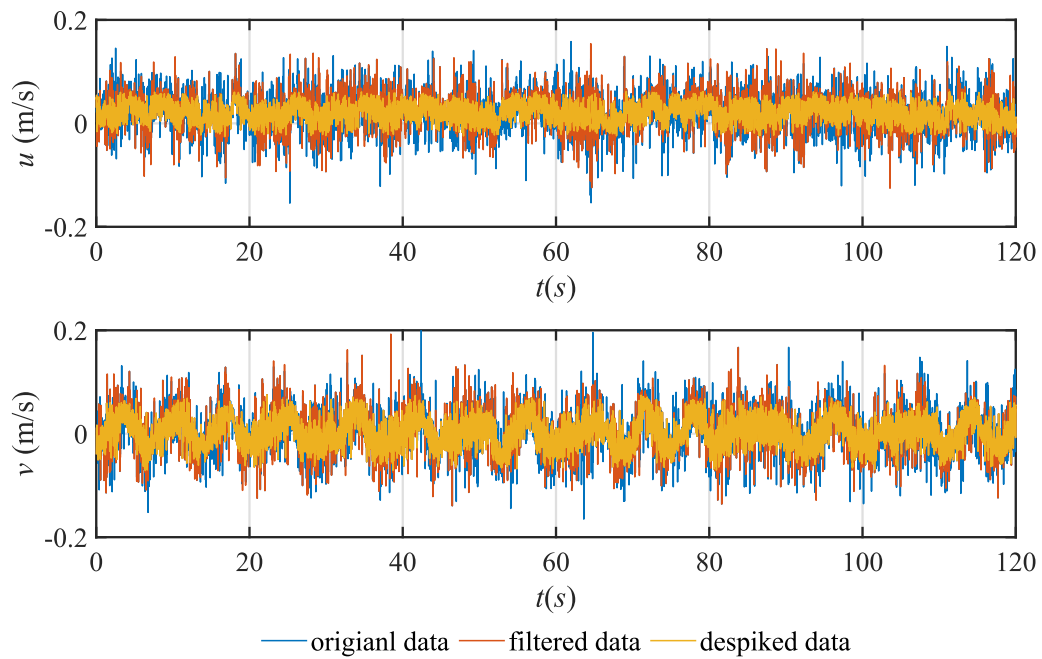


Figure 3.14: Data treatment. The example velocity data was collected behind a high-density vegetation patch with a small time-averaged velocity and high turbulence. Filtered data refers to the data in which records with a correlation coefficient below 70% were removed. Despiked data refers to velocity records from which spikes were removed using the method developed by Goring & Nikora (2002).

recording videos with 29.97 frames per second. In the mobile-bed experiments, which focused on the evolution of flow structures as the bedform developed, dyes of the same color were used for simplicity (Figure 3.16). As light was sufficiently available, no additional lighting was installed during the mobile-bed tests.

To describe the wake von Karman vortices, dye was injected at both corners of the trailing edge of the patch. The steady wake length ( $L_{d1}$ , subscript “d” indicating estimation from dye experiments) was estimated from the downstream end of the patch to the point where the two streaks of dye merge (Figure 3.15). The lengths extracted from all images were averaged to eliminate the oscillation of the mixing point due to the alternation of the vortex. The uncertainty was estimated from the standard deviation of the values measured from each image. To characterize the Kelvin-Helmholtz vortices, dye was released at the side interfaces of the patch (Figure 3.16). The vortex frequency was extracted from the videos. The time interval between two consequent vortices shedding to the same position (e.g., outermost) was recorded as the shedding period,  $T_d$  (Figure 3.17). Then, the vortex frequency can be estimated from the average of all observed values,  $f_{dye} = 1/T_d$ . The frequency extracted from the video was consistent with the dominant frequency presented in the PSD (Figure 3.18).

To maintain water clarity for dye visualization, the tank water was replaced after every two dye injections. Dye tests were conducted at various running times during the mobile-bed experiments. To minimize any impact on deformed bed during water replacement, only a portion of the colored water was drained, ensuring that the water surface remained approximately 10 cm above the bedform. The tank was then refilled with clean water and drained to the same level, and this dilution process was repeated several times until the water was sufficiently clear for the next dye test. To avoid sudden changes in flow that could affect the bedform, the water pump was gradually reduced to zero before water replacement and gradually increased to the target flow rate afterward.



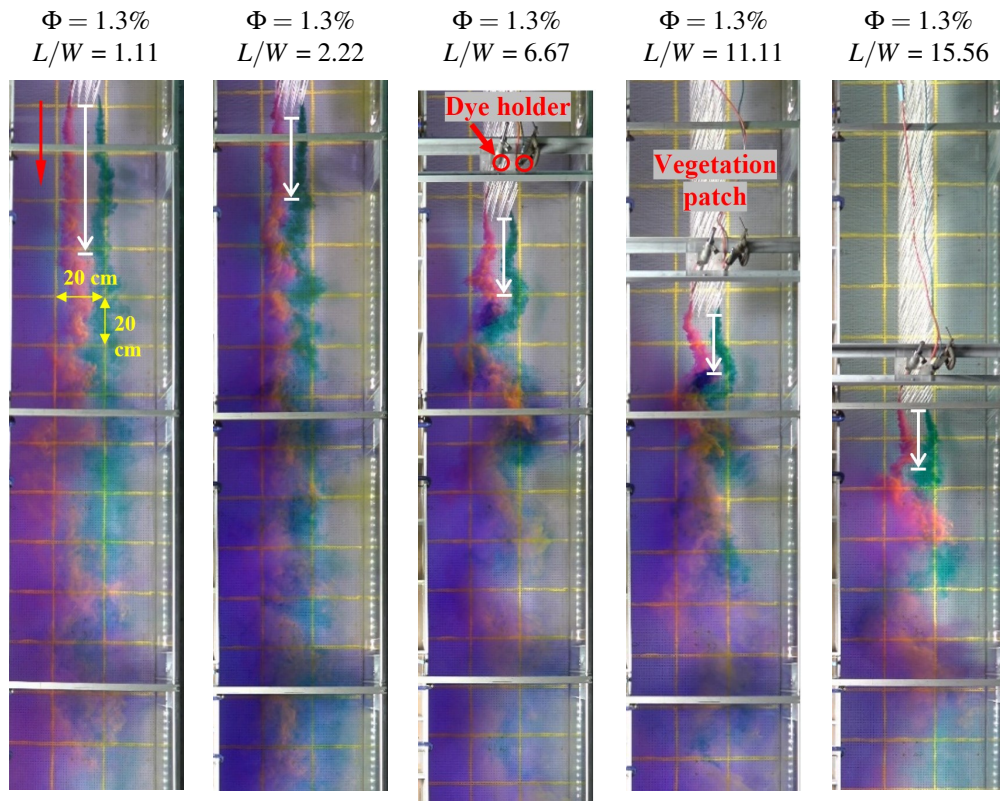


Figure 3.15: Dye visualization experiment on rigid bed. Flow is from top to bottom (red arrow). The dye was injected near the corners of the trailing edge. The yellow lines mark 20 cm intervals in both  $x$  and  $y$  directions (yellow arrows). The white arrows indicates the steady wake length ( $L_{d1}$ ).

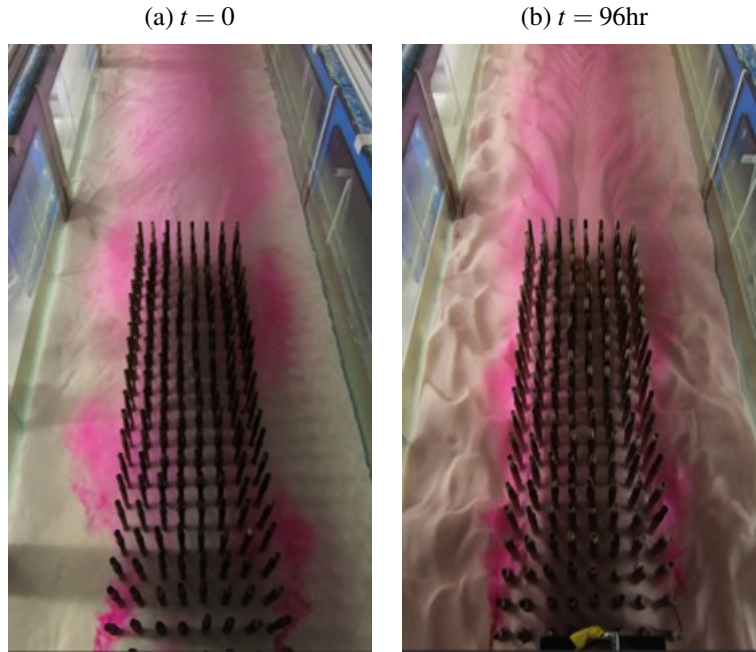


Figure 3.16: Dye visualization of Kelvin-Helmholtz (KH) vortices initiated at the lateral edges of an instream vegetation array on a mobile bed, observed at different running time: (a)  $t = 0$ , (b)  $t = 96$  hr. Dye was released approximately 1.5 m upstream of the trailing edge of the patch, where KH vortices were observed to be well-organized.

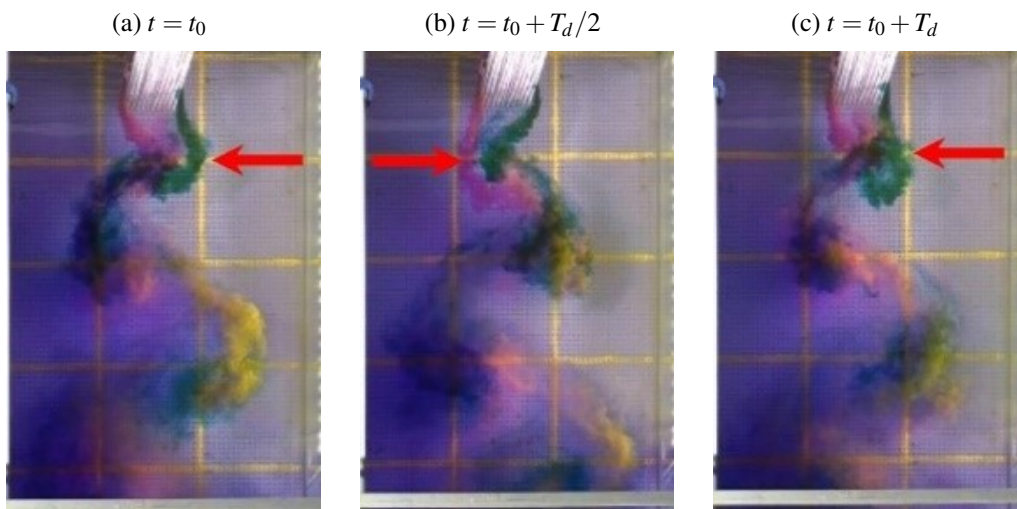


Figure 3.17: The estimation of Karman vortex shedding period,  $T_d$ .

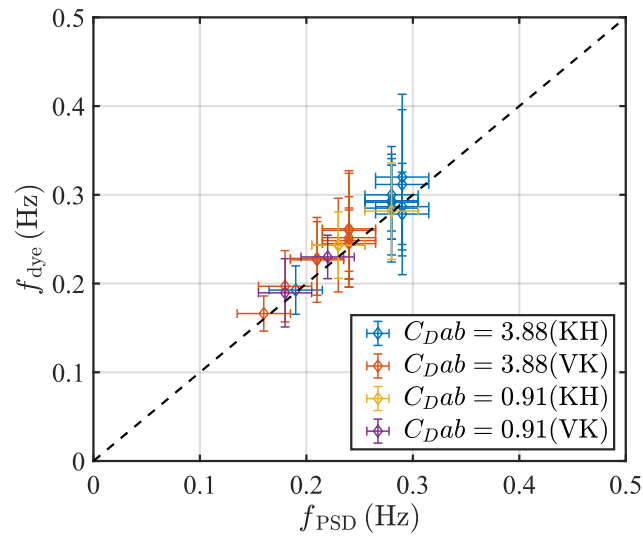


Figure 3.18: Comparison of vortex frequencies observed in the wake (von Karman vortex, labeled as ‘VK’ in the figure) and near the side edge (Kelvin–Helmholtz vortices, labeled as ‘KH’ in the figure), as extracted from video ( $f_{\text{dye}}$ ) and from power spectral density ( $f_{\text{PSD}}$ ). The dashed line is a 1:1 ratio. The figure confirms that the  $f_{\text{dye}}$  was consistent with  $f_{\text{PSD}}$ .

## Chapter 4

# The combined effects of patch density and length-to-width aspect ratio on wake structure behind a rectangular vegetation patch

### 4.1 Introduction

Initially, vegetation often appears in circular patches (Vandenbruwaene et al. 2011). The presence of a finite vegetation patch creates a steady wake region with reduced mean velocity and turbulent intensity behind the patches, which promotes net deposition (Chen, Ortiz, Zong & Nepf 2012) and facilitates the patches elongated in the streamwise direction (Vandenbruwaene et al. 2011). The presence of bleed flow delays the onset of the von Karman vortex street, relative to solid obstruction, leading to the presence of a steady wake region (Chang & Constantinescu 2015).

The patch dimensions could alter the flow motion by controlling the reach of the resistance of the vegetation. Thus, an elongated patch with a distinct lateral and longitudinal dimensions behaves differently compared to the circular ones with comparable streamwise and spanwise length scales. Specifically, increasing patch width ( $W$ ) may delay the lateral flow diversion, leading to an adverse effect on the interior velocity adjustment. However, the patch length ( $L$ ) controls the space for the velocity drop until the end of the interior adjustment region. Therefore, if the patch length is shorter than the interior adjustment length ( $L_i$ ), a continuous growth of lateral velocity gradient at the patch trailing edge will be presented as patch elongates downstream. In other words, larger patch length and vegetation density may lead to higher velocity reduction, but patch width presents the opposite impact. Therefore, in addition to vegetation density, patch aspect ratio ( $L/W$ ) should be a critical factor for flow behavior, which

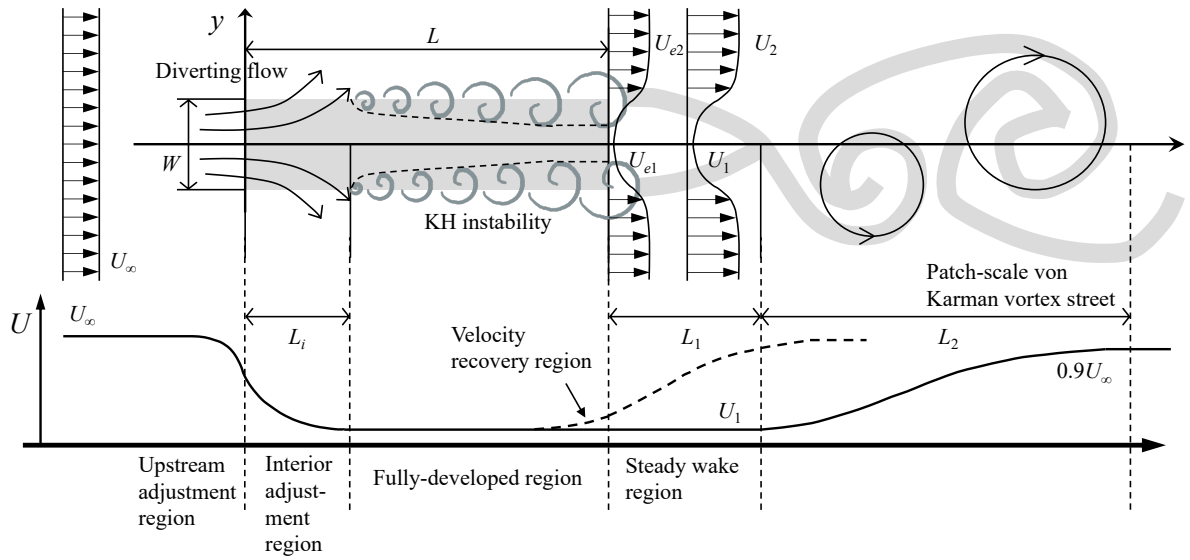


Figure 4.1: Conceptual diagram for flow structure near the vegetation patch (top) and the streamwise velocity adjustment along the patch centerline (bottom).

is distinct from a circular patch having only one typical dimension. The combined effect of vegetation density and patch aspect ratio may evaluate the cumulative hydraulic resistance. They affect the wake structure by changing the bleed flow velocity. Moreover, patch elongation may trigger the generation of Kelvin–Helmholtz (KH) instability along the patch lateral edges, which may impose some effects on the wake structure. Based on current findings, a schematic diagram showing the impact of a vegetation patch on the flow is shown in Figure 4.1. Therefore, it is significant to investigate the combined effect of patch aspect ratio and vegetation density. However, most previous studies focused on the wake vortex structure around circular patches and the effect of the vegetation elongation has not drawn enough interest or attention in literature (Zong & Nepf 2012, Chen, Ortiz, Zong & Nepf 2012, Li et al. 2019).

The presence of patch-scale von Karman vortex is highly related to the velocity difference between bleed flows from the patch and free stream, which is influenced by flow blockage (closely associated with vegetation density and patch dimensions) (Follett & Nepf 2012, Hu et al. 2018, Liu et al. 2018). When the velocity difference is fairly small, the vortex street will be ceased (White & Nepf 2007). Therefore, it is reasonably expected that patch elongation might facilitate the generation of wake vortex street even with a low vegetation density. Meanwhile, the delay effect of the bleed flow will be weakened due to its reduced velocity, thus the steady wake length is expected to be shortened as patch length increases. A numerical investigation of flow in a multi-cylinder tandem array has demonstrated that extending the length of porous obstruction promoted the formation of von Karman vortex street (Hosseini et al. 2020). Moreover, how the along-edge vortex structure interacts or impacts the wake vortex structure (e.g., frequency interaction) is also of great importance for the full understanding of flow-patch

interaction. The above arguments make it clear that the combined effect of vegetation density and aspect ratio are determinant to the flow velocity distribution pattern and the formation of vortex structure around and behind a vegetation patch. This concept differentiates from previous studies mainly addressing the role of vegetation density only (with comparable or fixed aspect ratio). Therefore, this chapter aims to extend this research direction, with aid of rigorous experimental works and in combination of former relevant results in literature, to highlight the combined effect of vegetation density and patch aspect ratio. The specific objectives of this chapter are:

- (i) to evaluate how the wake structure of a finite porous patch behaves under the changes in both solid volume fraction and aspect ratio of the patch;
- (ii) to understand the underlying mechanism of the formation and structure of the von Karman vortex street behind a porous patch, including patch interior adjustment and impact of KH instability;
- (iii) to identify and interpret the formation thresholds of the Karman vortex street behind a porous patch across a range of patch aspect ratios.

This chapter complements previous experimental works on wake structures behind circular porous patches (Zong & Nepf 2012, Chen, Ortiz, Zong & Nepf 2012) and relates it with the in-patch velocity adjustment (Rominger & Nepf 2011), expanding them in relation to the potential effects associated with patch aspect ratios. The objectives of this chapter were achieved by carrying out laboratory experiments by means of velocity measurement and flow visualization.

## 4.2 Materials and Methods

This chapter covered 25 tests with two patch widths ( $W$ ) of 0.09 m and 0.21 m, and varying lengths of  $L = 0.1 \sim 1.4$  m, leading to aspect ratios,  $L/W = 0.48 \sim 15.56$ . With such elongated rectangular patches, the importance of the cumulative resistance can be presented and the influences of longitudinal and lateral lengthscale can be differentiated. Note that the bottom friction may be an influencing factor on the generation of von Karman vortex street, which can be evaluated with a non-dimensional stability parameter  $S = c_f W/h$  (Chen & Jirka 1995). The vortex street will be inhibited when the stability parameter is over an observed critical value,  $S_c$ . In our experiments, the maximum value of  $S$  equals to 0.0010, which is much lower than  $S_c = 0.09$  for porous plate ( $\Phi = 0.5$ ) and  $S_c = 0.2$  for solid obstruction (Chen & Jirka 1995). Thus, bed friction was considered to not impact the formation of vortex formation in our experiment. All these test parameters are listed in Table 4.1. Sahin & Owens (2004) illustrated that the vortex shedding in the wake was similar to that of an unbounded condition when  $W/B < 0.5$ . In this regard, the values of  $W/B$  (0.15 and 0.35) in this section were smaller than 0.5, so that the boundary effect of channel sidewalls on the wake structure was negligible. The patches in

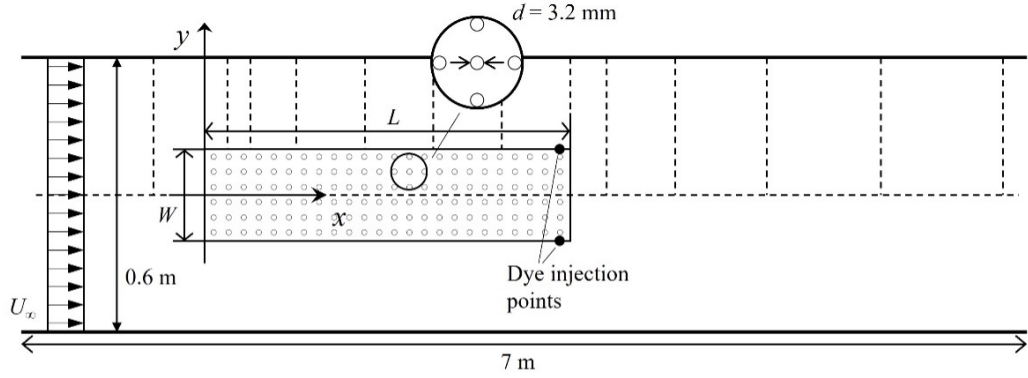
this section was configured with  $a = 3.6 \sim 16.0 \text{m}^{-1}$  and  $\Phi = 0.009 \sim 0.040$ , so that the patch flow-blockage ( $C_{Dab} = 0.16 \sim 0.72$ , where  $b$  is half width of the patch  $W/2$ , considering the drag coefficient  $C_D = 1$  for simplicity) for all cases were less than 1, falling into the low flow-blockage regime ( $C_{Dab} < 2$ ). Thus the adjustment length could be calculated by the patch drag length scale and patch half-width according to Equation (3.23), denoted as  $L_{i,c}$  (subscript “c” indicating estimation from calculation).

Table 4.1: Summary of experimental parameters.  $L$  is the length of the patch.  $W$  is the width of the patch.  $N$  is the number of rods per unit bed area.  $a$  is the frontal area per unit volume.  $\Phi$  is the average solid volume fraction.  $C_{Dab}$  is the patch flow-blockage with  $b$  is half width of the patch  $b = W/2$ .  $L_{i,c}$  is the calculated interior adjustment length according to Equation (3.23).

| Case | $L$<br>(m) | $W$<br>(m) | $N$<br>( $\text{m}^{-2}$ ) | $a = Nd$<br>( $\text{m}^{-1}$ ) | $\Phi$ | $C_{Dab}$ | $S = c_f W/h$ | $L_{i,c}$<br>(m) |
|------|------------|------------|----------------------------|---------------------------------|--------|-----------|---------------|------------------|
| A1   | 0.1        |            |                            |                                 |        |           |               |                  |
| A2   | 0.2        |            |                            |                                 |        |           |               |                  |
| A3   | 0.6        | 0.09       | 1111                       | 3.6                             | 0.009  | 0.16      | 0.0004        | $1.73 \pm 0.17$  |
| A4   | 1.0        |            |                            |                                 |        |           |               |                  |
| A5   | 1.4        |            |                            |                                 |        |           |               |                  |
| B1   | 0.1        |            |                            |                                 |        |           |               |                  |
| B2   | 0.2        |            |                            |                                 |        |           |               |                  |
| B3   | 0.6        | 0.09       | 1667                       | 5.3                             | 0.013  | 0.24      | 0.0004        | $1.19 \pm 0.12$  |
| B4   | 1.0        |            |                            |                                 |        |           |               |                  |
| B5   | 1.4        |            |                            |                                 |        |           |               |                  |
| Bw1  | 0.1        |            |                            |                                 |        |           |               |                  |
| Bw2  | 0.2        |            |                            |                                 |        |           |               |                  |
| Bw3  | 0.6        | 0.21       | 1667                       | 5.3                             | 0.013  | 0.36      | 0.0010        | $1.48 \pm 0.15$  |
| Bw4  | 1.0        |            |                            |                                 |        |           |               |                  |
| Bw5  | 1.4        |            |                            |                                 |        |           |               |                  |
| C1   | 0.1        |            |                            |                                 |        |           |               |                  |
| C2   | 0.2        |            |                            |                                 |        |           |               |                  |
| C3   | 0.6        | 0.09       | 2500                       | 8.0                             | 0.02   | 0.56      | 0.0004        | $0.85 \pm 0.08$  |
| C4   | 1.0        |            |                            |                                 |        |           |               |                  |
| C5   | 1.4        |            |                            |                                 |        |           |               |                  |
| D1   | 0.1        |            |                            |                                 |        |           |               |                  |
| D2   | 0.2        |            |                            |                                 |        |           |               |                  |
| D3   | 0.6        | 0.09       | 5000                       | 16.0                            | 0.04   | 0.72      | 0.0004        | $0.57 \pm 0.06$  |
| D4   | 1.0        |            |                            |                                 |        |           |               |                  |
| D5   | 1.4        |            |                            |                                 |        |           |               |                  |

Velocity measurements were taken using a three-dimensional Nortek Vectrino Profiler. More detailed information related to the data collection and ADV configuration can be seen in Sec-

(a)



(b)

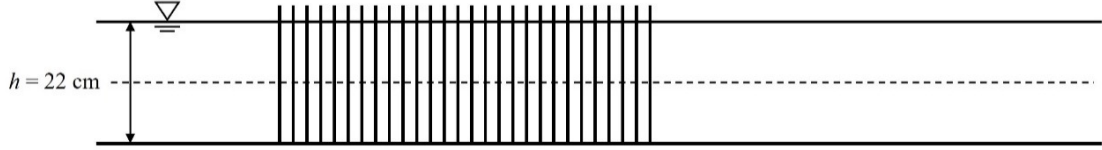


Figure 4.2: Experimental setup. (a) Top view. Patch configuration and dye injection points, longitudinal and lateral transects (dashed lines) of velocity measurements. (b) Side view. Velocity measurements were conducted at the middle of the water depth.

tion 3.5. This section applies a right-handed coordinate system, with the origin at the channel bottom, in the middle of the leading edge of the patch (Figure 4.2). The positions of measurement transects were denoted by the dashed lines in Figure 4.2. The longitudinal adjustment of flow velocity was assessed by measurements along the centerline of the flume. Considering the length and density of the patches, the measurements covered a region from 0.6 m upstream to 4.5 m downstream from the leading edge ( $x = -0.6 \text{ m} \sim 4.5 \text{ m}$ ) with neighboring intervals of  $5 \sim 20 \text{ cm}$ . Smaller intervals were applied to the regions with larger velocity gradients (e.g., leading edge and velocity recovery region). The lateral adjustment of flow was assessed by measurements along several transects along the flume, which covered the region of KH vortices and wake vortex street. The lateral measurement intervals were  $1 \sim 3 \text{ cm}$ , ensuring that lower intervals were applied to the higher velocity gradient region (lateral edges of the patch). In particular, as the velocity at the trailing edge highlights the flow characteristics for porous-patch flows, lateral measurements of velocities were made for every case. The lateral measurements were only conducted in one half of the flume due to symmetry configuration.

For the analysis of velocity measurements, the distance from the patch leading edge ( $x = 0$ ) to the position where the velocity achieves an equilibrium or starts to increase within the patch is defined as measured interior adjustment length,  $L_{i,m}$ , (the subscript “ $m$ ” here indicates the estimation from measurements). The steady wake length,  $L_1$ , is estimated from the longitudinal velocity profile as the distance from the downstream end of the patch to the position where the velocity begins to increase, indicating the formation position of the vortex street. The dis-



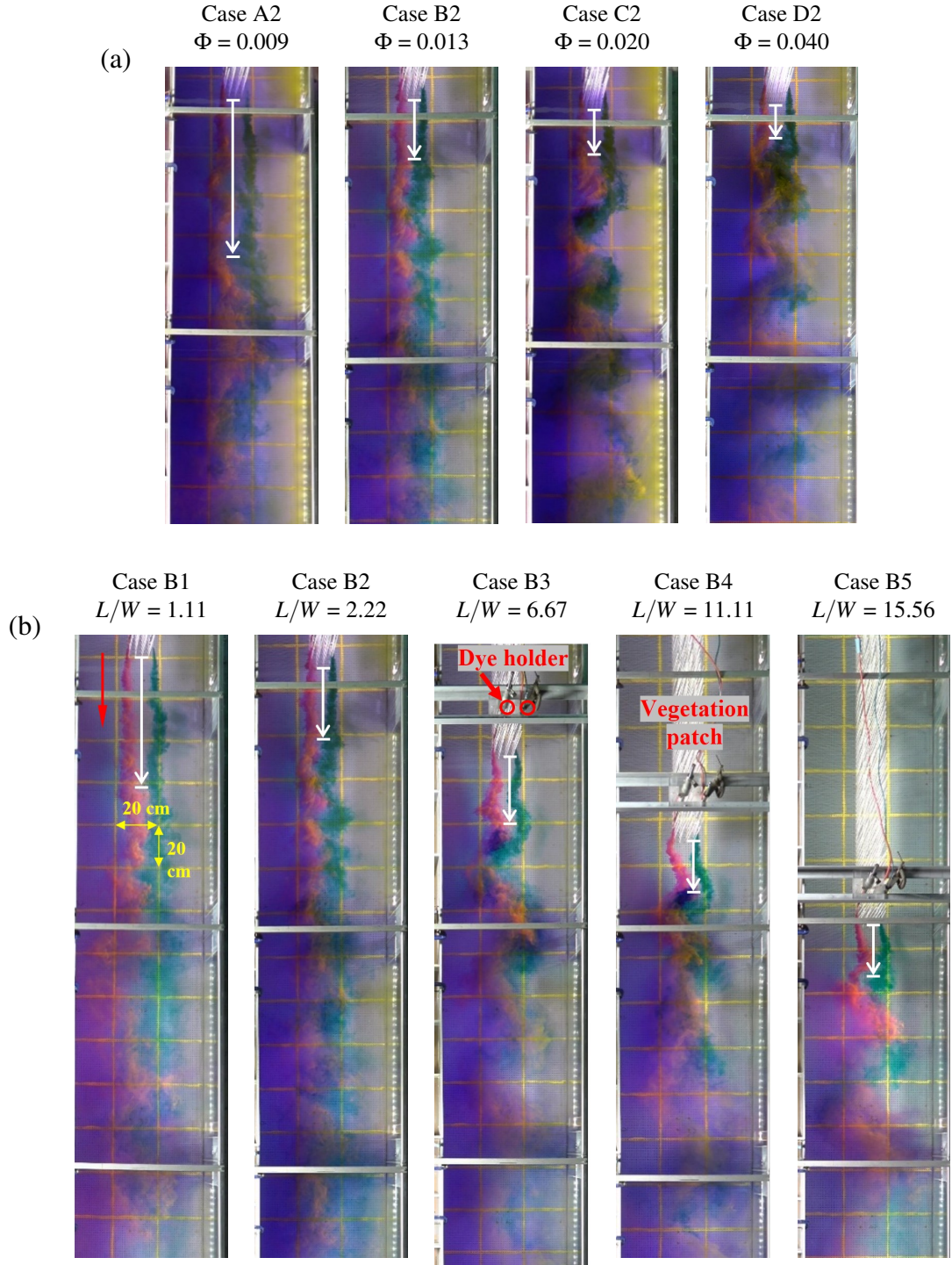


Figure 4.3: Dye visualization experiment. The impact of (a) solid volume fraction for  $L/W = 2.22$ . (b) patch elongation for  $\Phi = 0.013$ . Flow is from top to bottom (red arrow). The dye was injected near the corners of the trailing edge. The yellow lines mark 20 cm intervals in both  $x$ - and  $y$ -direction (yellow arrows). The white arrows indicates the steady wake length ( $L_{d1}$ ).

tance from the end of steady wake region to a point where the velocity is recovered to 90% of the mean upstream velocity,  $U_\infty$ , is defined as the wake recovery (wake decay) length  $L_2$ . The uncertainty of the evaluation of  $L_1$  and  $L_2$  is induced by the measurement spacing at that point.  $U_1$  is the mean streamwise velocity at  $x = L + L_1$ ,  $y = 0$  and  $U_2$  is the unchanged mean streamwise velocity in the non-vegetation region at corresponding  $x$  transect. The recovery rate (spatial acceleration) of recovery region is defined as  $(U_\infty - U_1)/L_2$ . Similarly,  $U_{e1}$  is the mean streamwise velocity at the central point of the patch trailing edge, and  $U_{e2}$  is defined as the mean streamwise velocity at the open area at the same transect, i.e.,  $x = L$ . All these velocities defined here were time-averaged and measured at mid-depth of the water height. These definitions have been largely discussed and used by Chen, Ortiz, Zong & Nepf (2012) and Zong & Nepf (2012). The previous attentions, however, were focused on circular patches with comparable longitudinal and transverse length dimensions. For an elongated patch, the similar definitions are applied herein. All these definitions can be seen in Figure 4.1.

## 4.3 Results

### 4.3.1 Hydrodynamic adjustment

Time-averaged streamwise velocities ( $\bar{u}$ ) along the channel centerline were measured under different patch solid volume fractions ( $\Phi$ , Figure 4.4) and aspect ratios ( $L/W$ , Figure 4.5). To highlight the degree of impact caused by the presence of the patches, the velocity is normalized by upstream unaffected velocity ( $U_\infty$ ). It is clearly observed that the flow velocity has been adjusted in response to the blocking effect of a porous patch centered on the flume. Streamwisely, the velocity adjustment, initially occurring in front of the patch, displays an apparent decay through the patch and recovered in the wake area for all scenarios. The velocity drop is more sensitive to  $\Phi$  rather than to  $L$ . In other words, under the same  $L$ , an earlier and larger drop occurs at a larger  $\Phi$  (Figure 4.4) but the velocity drops presented in the longitudinal velocity profiles nearly show an overlap for cases under the same  $\Phi$  (Figure 4.5).

After entering the patch, the whole patch falls within the adjustment region when  $L < L_i$ , where the velocity keeps decreasing with the same rate under the same  $\Phi$  (Figure 4.5). However, larger  $\Phi$  leads to more pronounced velocity drop (Figure 4.4). Moreover,  $L_i$  becomes smaller as  $\Phi$  increases, which follows the observations of flow adjustment within a long patch (Rominger & Nepf 2011). For longer patches, velocity adjustment completes within the patches, indicating  $L \geq L_i$ , and once the velocity minimum is achieved, the flow shifts to re-acceleration. This velocity recovery behavior within the patch attributed to lateral KH vortex interaction is similar to the results of some cases reported by Rominger & Nepf (2011). Clearly, a larger  $\Phi$  tends to promote the re-acceleration within the patches, indicating the enhancement of the parallel

lateral KH vortex interaction under larger  $\Phi$ . In particular, a larger  $W$  tends to effectively attenuate the velocity decay process due to mass conservation (Cases B,  $W = 0.09\text{m}$  vs Cases Bw,  $W = 0.21\text{m}$ , Figure 4.4). Furthermore, widening the patch tends to increase  $L_i$ , which is also consistent with the statistical relationship of  $L_i$ ,  $C_{Da}$  and  $W/2$  developed by Rominger & Nepf (2011). Theoretically, widening the patch decreases the aspect ratio ( $L/W$ ) which should be comparable to the scenarios of shortening the patch under a fixed width, which is analyzed in the following.

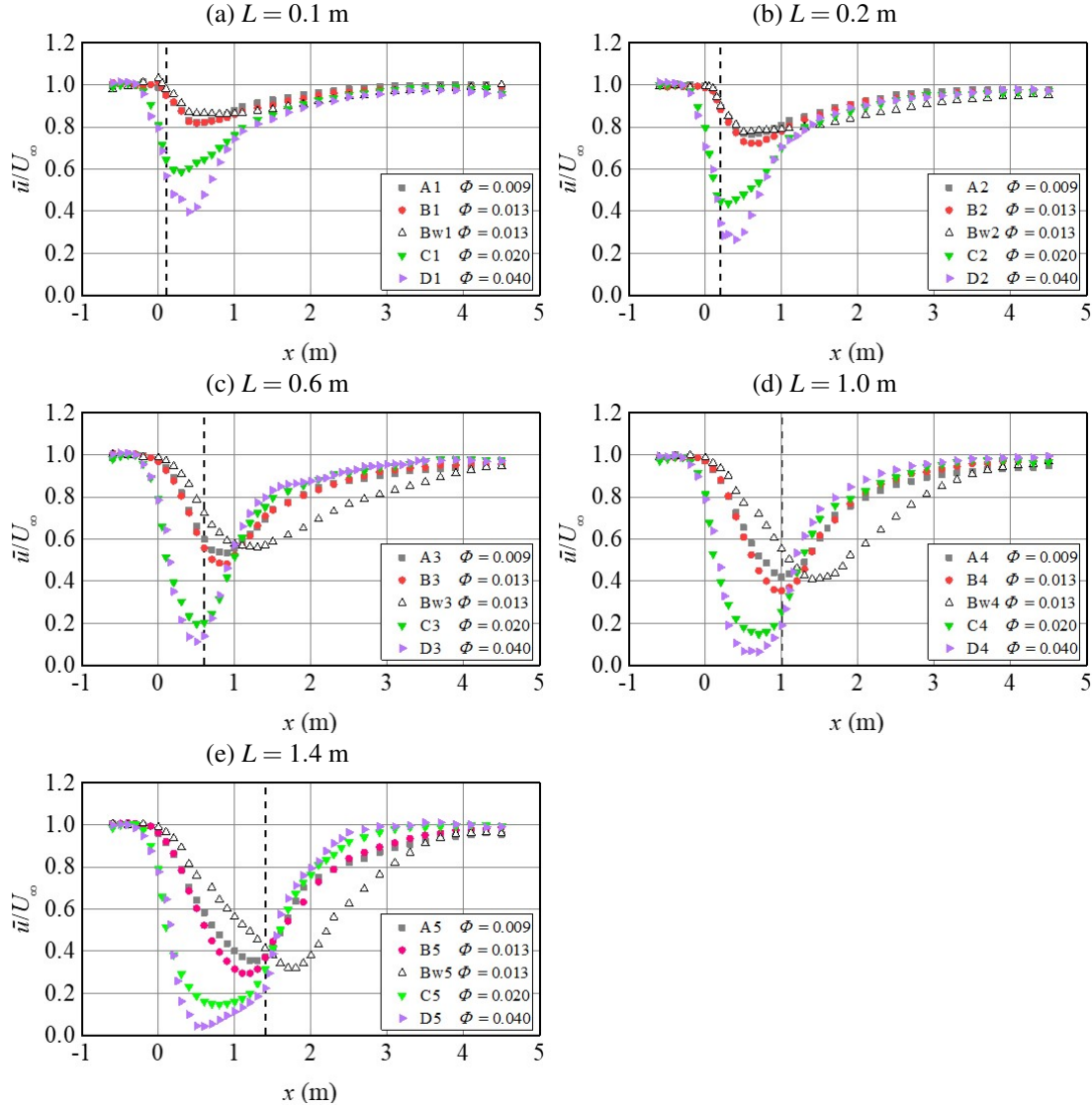


Figure 4.4: Longitudinal profiles of velocity for patches under the same length (a)  $L = 0.1$  m, (b)  $L = 0.2$  m, (c)  $L = 0.6$  m, (d)  $L = 1.0$  m, (e)  $L = 1.40$  m. The dashed lines indicate the trailing edges of the patches. The longitudinal velocity is measured at the patch centerline,  $y = 0$ .

For a constant  $\Phi$ , the overlapping region of the velocity adjustment under variable  $L/W$  (as shown in Figure 4.5) ends as the velocity starts to recover, indicating that the downstream

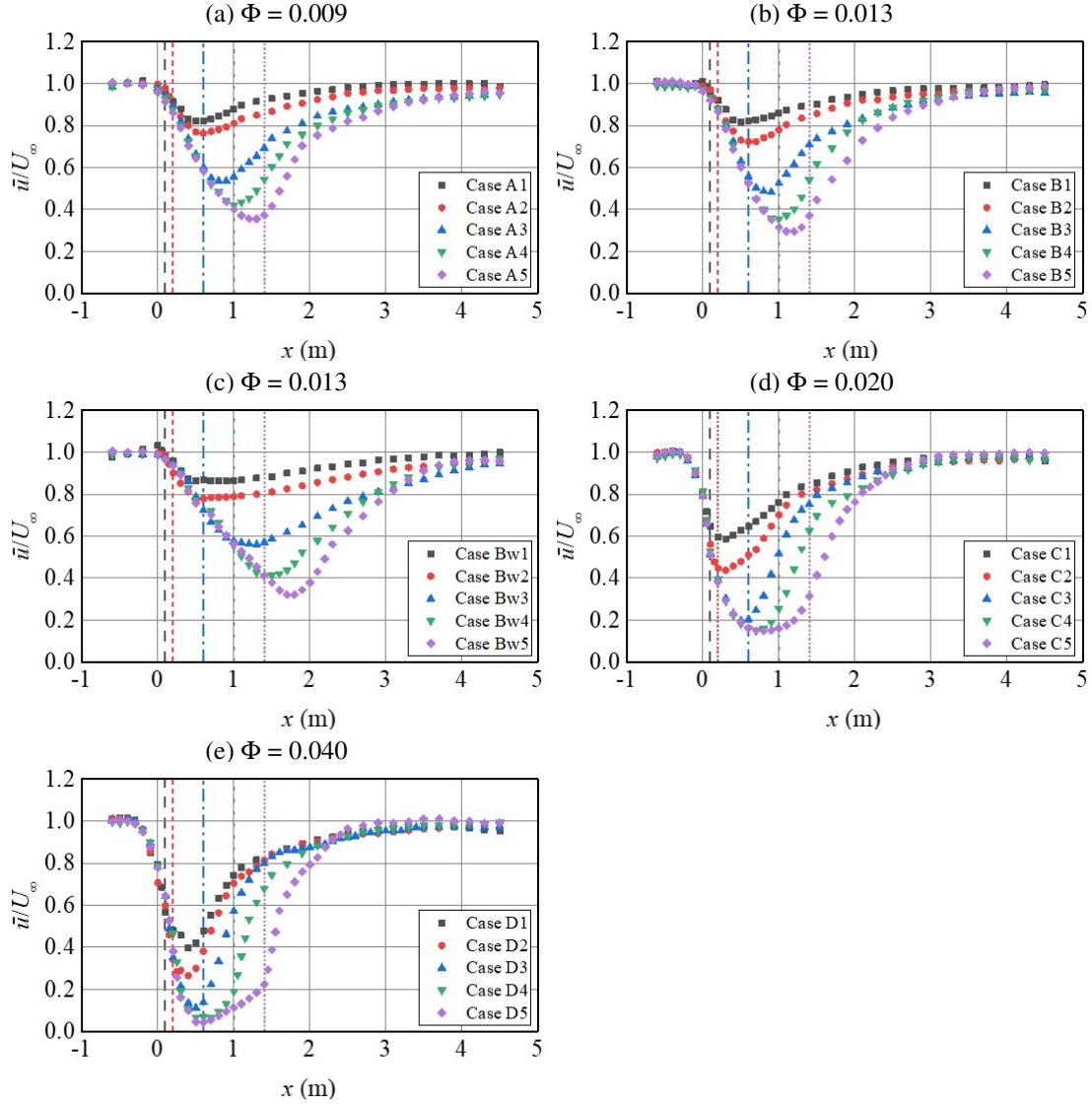


Figure 4.5: Longitudinal profiles of velocity for patches under the same  $\Phi$  (a) Case A ( $\Phi = 0.009$ ), (b) Case B ( $\Phi = 0.013$ ), (c) Case Bw ( $\Phi = 0.013$ ), (d) Case C ( $\Phi = 0.020$ ), (e) Case D ( $\Phi = 0.040$ ). The dashed lines with corresponding color of the case indicate the trailing edges of the patches with  $L = 0.10$  m,  $0.20$  m,  $0.60$  m,  $1.0$  m,  $1.4$  m from left to right. The longitudinal velocity is measured along the patch centerline,  $y = 0$ .

flow dynamics are negligibly influential to the upstream region for a vegetation-patch flow. This also confirms the analytical solution, developed by Liu et al. (2020), of the longitudinal velocity profile along a near-bank patch. As noted above, as the patch continuously elongates, the velocity decay tends to cease from the after-patch region ( $x > L$ ) to the in-patch region ( $x < L$ ) with a continuous reduction of the minimum velocity, opposite to widening the patch. As observed above (Cases Bw in Figure 4.4), the patches with larger  $W$  tend to present a larger minimum velocity though longer decay length. The essence for this behavior is that the increase in aspect ratio ( $L/W$ ) shall promote the interior flow adjustment.

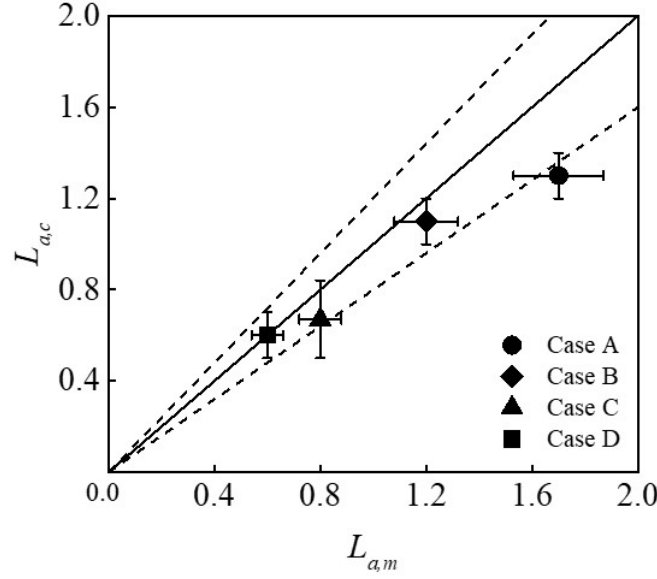


Figure 4.6: Comparison between  $L_{i,c}$  and  $L_{i,m}$ . The dashed lines indicated the 80% confidence intervals.

The interior adjustment lengths observed from longitudinal profiles of streamwise velocity,  $L_{i,m}$ , agree well with those calculated from the formula developed by Rominger & Nepf (2011),  $L_{i,c}$  (Figure 4.6). This consistency confirms no sidewall effect on the in-patch velocity adjustment. It is also noted that  $L_i$  is independent of  $L$  (Rominger & Nepf 2011, Chen et al. 2013, Kim, Kimura & Shimizu 2015), thus each  $L_{i,m}$  is averaged among cases with varying  $L$  but same  $\Phi$  once  $L \geq L_i$  (i.e., Case D stands for the mean value for Cases D3 ~ D5 in Table 4.2). For Case A ( $\Phi = 0.009$ ), fully developed region only occurs in Case A5 ( $L = 1.4$  m) and its  $L_{i,m} = 1.3 \pm 0.1$  m. Thus, Case A presents a relatively larger deviation mainly due to insufficient measurement density. Flow within Cases Bw is not fully developed, according to either calculated  $L_{i,c}$  or measured  $L_{i,m}$ , which is not plotted in Figure 4.6.

The wake structure at  $x = L + L_1$  for cases with different lengths is evaluated by the lateral profiles of  $\bar{u}/U_\infty$  given in Figure 4.7 and normalized Reynolds shear stress  $(-\overline{u'v'})/u_*^2$ , where  $u_*$  is the friction velocity) in Figure 4.8. When the patch length is smaller than the interior adjustment length, velocity keeps decreasing within the patch, thus steady wake velocity decreases

Table 4.2: Measured parameters. VK and KH indicate the presence (Y) or absence (N) of Karman vortex street and Kelvin-Helmholtz vortex street respectively.

| Case | $U_1$<br>(cm/s) | $U_2$<br>(cm/s) | $L_1$<br>(m) | $L_2$<br>(m) | $L_{d1}$<br>(m) | $U_{e1}$<br>(cm/s) | $U_{e2}$<br>(cm/s) | (VK, KH) | $L_{i,m}$<br>(m) | $L_K$<br>(m) | $f_{VK}$<br>(Hz) | $f_{dye}$<br>(Hz) | $f_{KH}$<br>(Hz) |
|------|-----------------|-----------------|--------------|--------------|-----------------|--------------------|--------------------|----------|------------------|--------------|------------------|-------------------|------------------|
| A1   | 6.6             | 8.4             | $\pm 0.1$    | 1.3          | 0.9             | $\pm 0.4$          | 7.6                | 8.5      | (N, N)           | -            | -                | -                 | -                |
| A2   | 6.1             | 8.7             | $\pm 0.1$    | 1.9          | 0.8             | $\pm 0.4$          | 7.1                | 8.5      | (N, N)           | -            | -                | -                 | -                |
| A3   | 4.3             | 9.4             | $\pm 0.1$    | 3.4          | 0.4             | $\pm 0.2$          | 4.8                | 9.3      | (Y, N)           | 0.23         | 0.19             | 0.2               | -                |
| A4   | 3.4             | 9.8             | $\pm 0.1$    | 3.5          | 0.3             | $\pm 0.3$          | 3.4                | 9.8      | (Y, N)           | 0.24         | 0.14             | 0.17              | -                |
| A5   | 3               | 9.9             | $\pm 0.1$    | 2.5          | 0.2             | $\pm 0.2$          | 3                  | 9.9      | (Y, Y)           | 1.3          | 0.20             | 0.15              | 0.13             |
| B1   | 6.6             | 8.5             | $\pm 0.1$    | 1.5          | 1               | $\pm 0.4$          | 7.6                | 8.3      | (N, N)           | -            | -                | -                 | -                |
| B2   | 5.8             | 8.5             | $\pm 0.1$    | 2.0          | 0.6             | $\pm 0.3$          | 7.1                | 8.8      | (N, N)           | -            | -                | -                 | -                |
| B3   | 3.9             | 9.5             | $\pm 0.1$    | 2.8          | 0.3             | $\pm 0.3$          | 4.5                | 9.4      | (Y, N)           | 0.24         | 0.16             | 0.14              | -                |
| B4   | 2.8             | 9.7             | $\pm 0.1$    | 2.3          | 0.2             | $\pm 0.2$          | 2.8                | 9.7      | (Y, N)           | 0.20         | 0.14             | 0.14              | -                |
| B5   | 3               | 10.2            | $\pm 0.1$    | 2.1          | 0.2             | $\pm 0.2$          | 3                  | 10.2     | (Y, Y)           | 1.1          | 0.21             | 0.14              | 0.13             |
| Bw1  | 6.9             | 8.8             | $\pm 0.1$    | 1.4          | -               | -                  | 7.9                | 8.7      | (N, N)           | -            | -                | -                 | -                |
| Bw2  | 6.3             | 9.3             | $\pm 0.1$    | 2.8          | 1.1             | $\pm 0.3$          | 7.2                | 9.2      | (N, N)           | -            | -                | -                 | -                |
| Bw3  | 4.6             | 10.7            | $\pm 0.1$    | 3.1          | 0.7             | $\pm 0.3$          | 5.8                | 10.8     | (Y, N)           | 0.29         | 0.16             | -                 | -                |
| Bw4  | 3.3             | 11.2            | $\pm 0.1$    | 2.6          | 0.4             | $\pm 0.3$          | 4.4                | 11.9     | (Y, N)           | 0.28         | 0.12             | 0.14              | -                |
| Bw5  | 2.6             | 11.9            | $\pm 0.1$    | 2.1          | 0.3             | $\pm 0.2$          | 3.3                | 12.2     | (Y, N)           | 0.22         | 0.12             | 0.13              | -                |
| C1   | 4.7             | 8.7             | $\pm 0.1$    | 2.2          | 0.4             | $\pm 0.1$          | 5.2                | 8.6      | (N, N)           | -            | -                | -                 | -                |
| C2   | 3.5             | 9.1             | $\pm 0.1$    | 2.6          | 0.3             | $\pm 0.3$          | 3.6                | 9.1      | (Y, N)           | -            | 0.19             | 0.17              | -                |
| C3   | 1.6             | 9.9             | $\pm 0.1$    | 2.5          | 0.1             | $\pm 0.2$          | 1.6                | 9.9      | (Y, N)           | 0.5          | 0.10             | 0.16              | 0.17             |
| C4   | 2               | 10.2            | $\pm 0.1$    | 2.1          | 0.1             | $\pm 0.2$          | 2                  | 10.2     | (Y, Y)           | 0.7          | 0.13             | 0.15              | 0.17             |
| C5   | 2.5             | 10.5            | $\pm 0.1$    | 1.5          | 0.1             | $\pm 0.2$          | 2.5                | 10.5     | (Y, Y)           | 0.8          | 0.18             | 0.14              | 0.17             |
| D1   | 3.2             | 9.3             | $\pm 0.1$    | 2.3          | 0.3             | $\pm 0.2$          | 4.5                | 9.1      | (Y, N)           | -            | 0.18             | 0.18              | 0.2              |
| D2   | 2.1             | 9.9             | $\pm 0.1$    | 2.7          | 0.2             | $\pm 0.2$          | 2.7                | 9.4      | (Y, N)           | -            | 0.11             | 0.19              | 0.2              |
| D3   | 1.1             | 10.2            | $\pm 0.1$    | 2.1          | 0.1             | $\pm 0.2$          | 1.1                | 10.2     | (Y, Y)           | 0.5          | 0.08             | 0.14              | 0.17             |
| D4   | 1.5             | 10.2            | $\pm 0.1$    | 1.7          | 0.1             | $\pm 0.2$          | 1.5                | 10.2     | (Y, Y)           | 0.7          | 0.11             | 0.14              | 0.14             |
| D5   | 1.8             | 7.8             | $\pm 0.1$    | 1.1          | 0.1             | $\pm 0.2$          | 1.8                | 10.6     | (Y, Y)           | 0.6          | 0.12             | 0.15              | 0.14             |



as patch length increases (i.e., larger velocity deficit) (Figure 4.7a). However, when the interior velocity adjustment is completed within the patch (interior adjustment length  $<$  patch length), the velocity presents a recovery region after the interior adjustment region. Because interior adjustment length is constant under the same vegetation density and patch width, larger patch length results in longer velocity recovery region. The velocity deficit appears to reduce due to the velocity recovery. Thus, a peak velocity deficit presents when patch elongates downstream (Figure 4.7b). In summary, the velocity deficit may keep growing (before fully interior velocity adjustment) or present a peak (after fully interior velocity adjustment) as patch length increases, consistent with the results shown in Figure 4.5. Additionally, if the peak exists, the peak will present earlier (under smaller patch length) when  $\Phi$  increases. That's because vegetation density may speed up the interior velocity adjustment and shorten the interior adjustment length. For instance, velocity deficit peaks at  $L = 1.0$  m for Case B ( $\Phi = 0.013$ ) while it shifts to  $L = 0.6$  m for Case D ( $\Phi = 0.020$ ). The peak of the normalized Reynolds shear stress is located outside the patch edge, which is a signature of a shear layer (Figure 4.8). Maximum normalized Reynolds shear stress value shows a monotonically increasing trend as the patch length increases, except for the Cases from D4 to D5 (Figure 4.8b). For sparse patch with relatively low density (Cases A1, B1, C1) or/and short length (Cases A2, B2), no peak presents in lateral profile of normalized Reynolds shear stress, implying no shear layer formed.

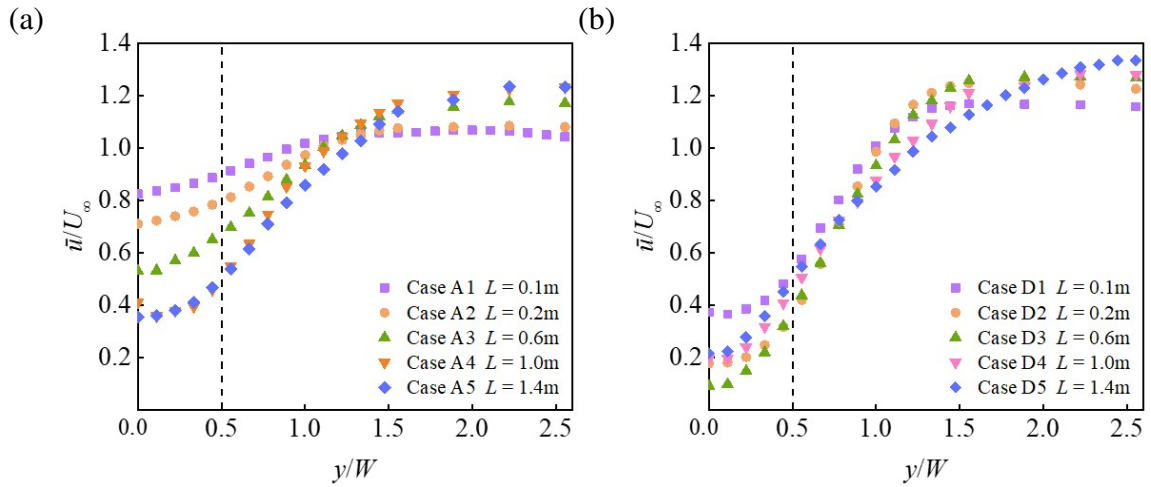


Figure 4.7: Lateral profiles of  $\bar{u}/U_\infty$  for (a) Case A ( $\Phi = 0.009$ ), (b) Case D ( $\Phi = 0.040$ ) at  $x = L + L_1$ . Owing to the symmetry about the centerline ( $y/W = 0$ ), measurements were only made on one side of the flume ( $0 < y/W < 2.56$ ). The black dashed line shows the patch edge.

### 4.3.2 Wake vortex structure

According to dye visualization (Figure 4.3), the increase in  $\Phi$  ( $0.009 \sim 0.040$ ) gradually encourages the formation of wake vortex streets (Figure 4.3a). The obvious alternation observed

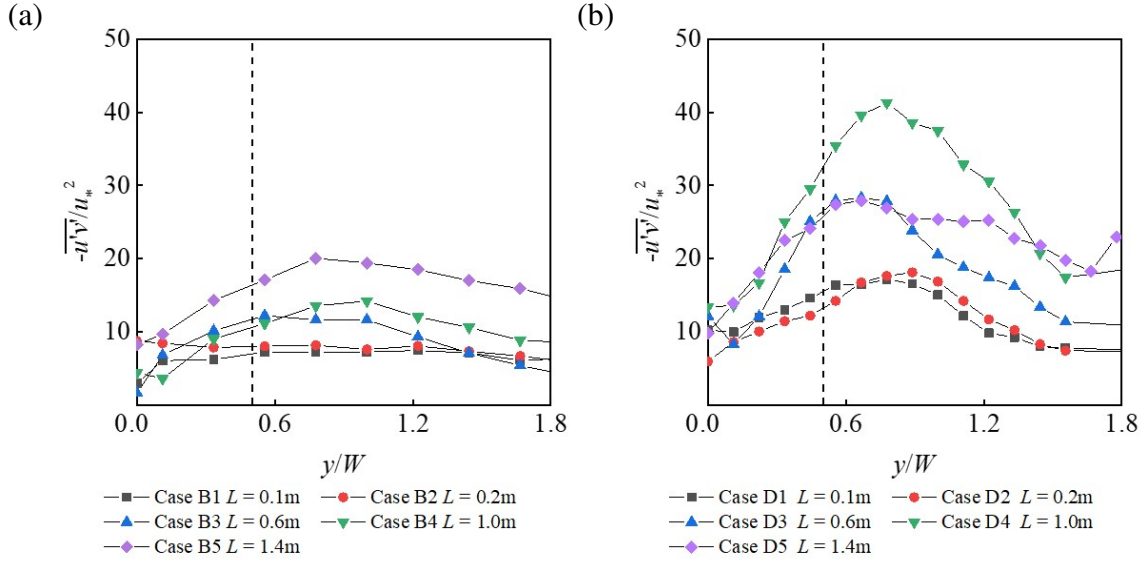


Figure 4.8: Lateral profiles of normalized Reynolds stress  $-\overline{u'v'}/u_*^2$  for (a) Case B ( $\Phi = 0.013$ ), (b) Case D ( $\Phi = 0.040$ ) at  $x = L + L_1$ . The black dashed line shows the patch edge.

at  $\Phi = 0.020$  (Case C2) is weakened for lower  $\Phi$  ( $= 0.013$ , Case B2) and even cannot be detected when  $\Phi = 0.009$  (Case A2). This oscillation with no alternation in Case A2 is likely attributed to local shearing and transverse diffusion (Chen & Jirka 1995, Uijttewaal & Booij 2000), while the wake instability is not eventually attained. Meanwhile, the increase in  $\Phi$  tends to accelerate the mixing of free parallel streams, shortening of the steady wake region ( $L_{d1}$ ). In fact, the effect of solid volume fraction on the wake vortex street observed herein is consistent with the existing works such as Zong & Nepf (2012) and Liu et al. (2018). Similar to  $\Phi$  enhancement, patch elongation can enhance the turbulent behavior from local shearing and self-diffusion (Case B1,  $L/W = 1.11$ ) to small-scale transverse wake oscillations (Case B2,  $L/W = 2.22$ , Figure 4.3b). Furthermore, the horizontal extent (size) of the vortices (indicated by dye) is further enhanced by the continuous growth in patch length and patch density, but this growth seems to be suppressed by the water depth. This indicates that the wake structure is controlled by patch dimension as well as patch density.

Some deviations can be observed between dye-measured  $L_{d1}$  and velocity-measured  $L_1$  in Figure 4.9, though they are generally consistent. For small  $L_1$  (or  $L_{d1}$ ), the deviation may be caused by the initial velocity of the injected dyes. Thus, some distance is needed for the dye to adjust to the ambient flow condition, which delays the mixing of the dyes (i.e.,  $L_{d1} > L_1$ ). However, for larger  $L_1$  (or  $L_{d1}$ ), the mixing point is possibly a result of the diffusivity of the dyes rather than the vortex shedding, leading to a larger difference. Furthermore, the  $L_{d1}$  estimated by eye detection also causes some uncertainties. The vortex frequency estimated from dye visualization ( $f_{dye}$ ) ranges from 0.13 to 0.20 Hz. For clarity, these statistical parameters and results are summarized in Table 4.2.



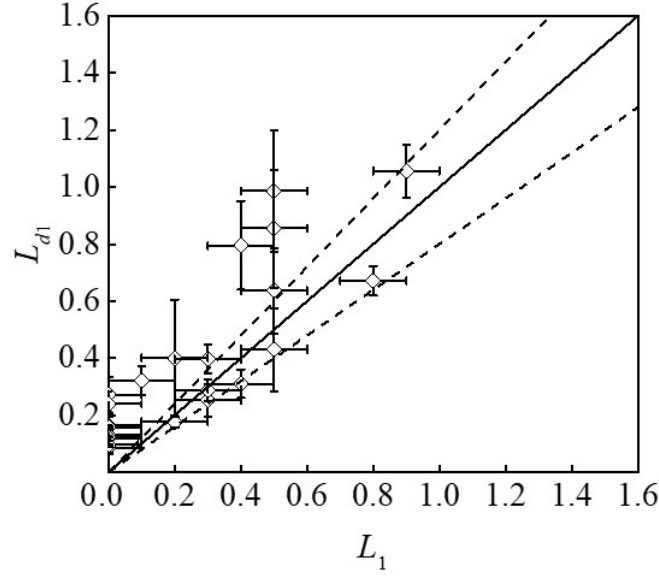


Figure 4.9: Comparison between  $L_1$  and  $L_{d1}$ .  $L_1$  is the length of steady wake measured from the longitudinal profile of  $\bar{u}$  at the patch centerline.  $L_{d1}$  is measured from dye images, and defined as the point at which the dye traces meet at the centerline. The dashed lines indicated the 80% confidence intervals.

The formation and coherence of the wake vortex characteristics can be described by the power spectral density of velocity (Bouris & Bergeles 1999, Park et al. 2006). The power spectral density of spanwise velocity ( $S_{vv}$ ) distributions along the patch centerline under varying  $L/W$  and  $\Phi$  are presented and compared in Figure 4.10. The dashed lines indicate the leading and trailing edges of the patch. The presence of the wake vortex street is indicated by a definite peak at low frequency  $f_{VK} = 0.12 \sim 0.19\text{Hz}$  after the patch, consistent well with those estimated from dye visualization ( $f_{dye}$ ) (Table 4.2). Similar vortex-shedding frequency ( $0.08 \sim 0.22\text{Hz}$ ) has been observed for circular patches (Zong & Nepf 2012, Hu et al. 2018, Liu et al. 2018). For the low  $\Phi = 0.009$  (i.e., Cases A), an apparent low-frequency peak arises in the spectra distribution while  $L/W \geq 6.67$  (Cases A3  $\sim$  A5), indicating that patch elongation can trigger the formation of the wake vortex street. Under higher  $\Phi$ , the aspect ratio required for the initiation of the wake vortex street will be lower, for instance, the wake vortex street occurs when  $L/W \geq 4.76$  and  $2.22$  for  $\Phi = 0.13$  (Cases B and Bw) and  $0.020$  (Cases C), respectively. Furthermore, the low-frequency peak occurs for all aspect ratios investigated here ( $L/W \geq 1.11$ ) for the high  $\Phi = 0.040$  (Cases D), evidencing the domination of high  $\Phi$  for vortex street formation.

In addition, the starting point of the peak migrates from the far-downstream region to directly behind the patch as  $L/W$  (e.g., Case C2 to C3) and  $\Phi$  (e.g., Case B3 to C3) increase, indicating the shortening of  $L_1$ . With sufficient  $L/W$  and  $\Phi$ , the peak even occurs within the patch with similar frequency, implying the presence of a Karman-like structure (due to the interaction of KH vortex streets along two patch side edges). This indicates that the formation

of Karman vortex street may be related to KH vortex streets, which will be discussed in section 4.2. However, due to the resistance induced by the vegetation stems, the intensity of this in-patch Karman-like structure is weaker than the after-patch Karman vortex street. After the patch, once the peak appeared, it decays during traveling downstream, indicating the decline of the wake vortex structure.

Turbulence theory indicates that the vortex characteristic length is inverse to vortex frequency (Pope 2000, Huai et al. 2015). In this experiment, the peak experiences a slightly smaller frequency (not obvious in Figure 4.10, but summarized in Table 4.2) and a stronger peak (shown in darker red in Figure 4.10) under a larger  $L/W$  and  $\Phi$ , demonstrating the enhancement of the vortex street. This promotion becomes less significant under high  $L/W$  and  $\Phi$ , likely due to the limitation of the water level. This observation is consistent with that shown in the dye visualization. According to Taylor's frozen turbulence assumption with the local time-averaged velocity ( $U_1$ ) as the convection velocity, the vortex wavelength (vortex spacing) can be estimated to be  $L_x = U_1/f_{VK} = 0.08 \sim 0.29$  m (Table 4.2). The vortex spacing shows a reverse trend to the velocity difference,  $(U_2 - U_1)$ , indicating that a higher velocity gradient leads to smaller vortex spacing. It demonstrates again that the vortex characteristics (frequency, vortex space, strength, etc.) are highly affected by the combined effects of patch aspect ratio and solid volume fraction.

## 4.4 Discussion

### 4.4.1 Wake structure related to patch density and aspect ratio

Our experimental measurements of hydrodynamic fields around a center-channel finite patch illustrate how flow velocity adjustment and wake structure respond to the vegetation patch under different cumulative resistance. The patch cumulative resistance is defined as the combined effect of solid volume fraction ( $\Phi$ ) and aspect ratio ( $L/W$ ), the latter of which has not yet drawn enough attention in previous studies. However, the aspect ratio of vegetation patch may vary significantly in nature due to vegetation colonization dynamics and different types of aquatic vegetation morphology (Gurnell 2014, Gran et al. 2015, Biggs et al. 2018, Yamasaki et al. 2019). The increase in patch density and aspect ratio can both decrease the pore velocity and thus increase the main flow velocity by meeting the balance between momentum flux, high drag and gravitational force in the patch. This enhances the velocity difference or gradient transversely, thereby promoting flow instability in the wake. However, it is identified that the global response of flow to these two factors are in essence distinct due to the shifting of the interaction between the patch and flow. From the perspective of momentum conservation, patch elongation affects the flow structure by expanding the reach of its source effect instead of intensifying this effect.

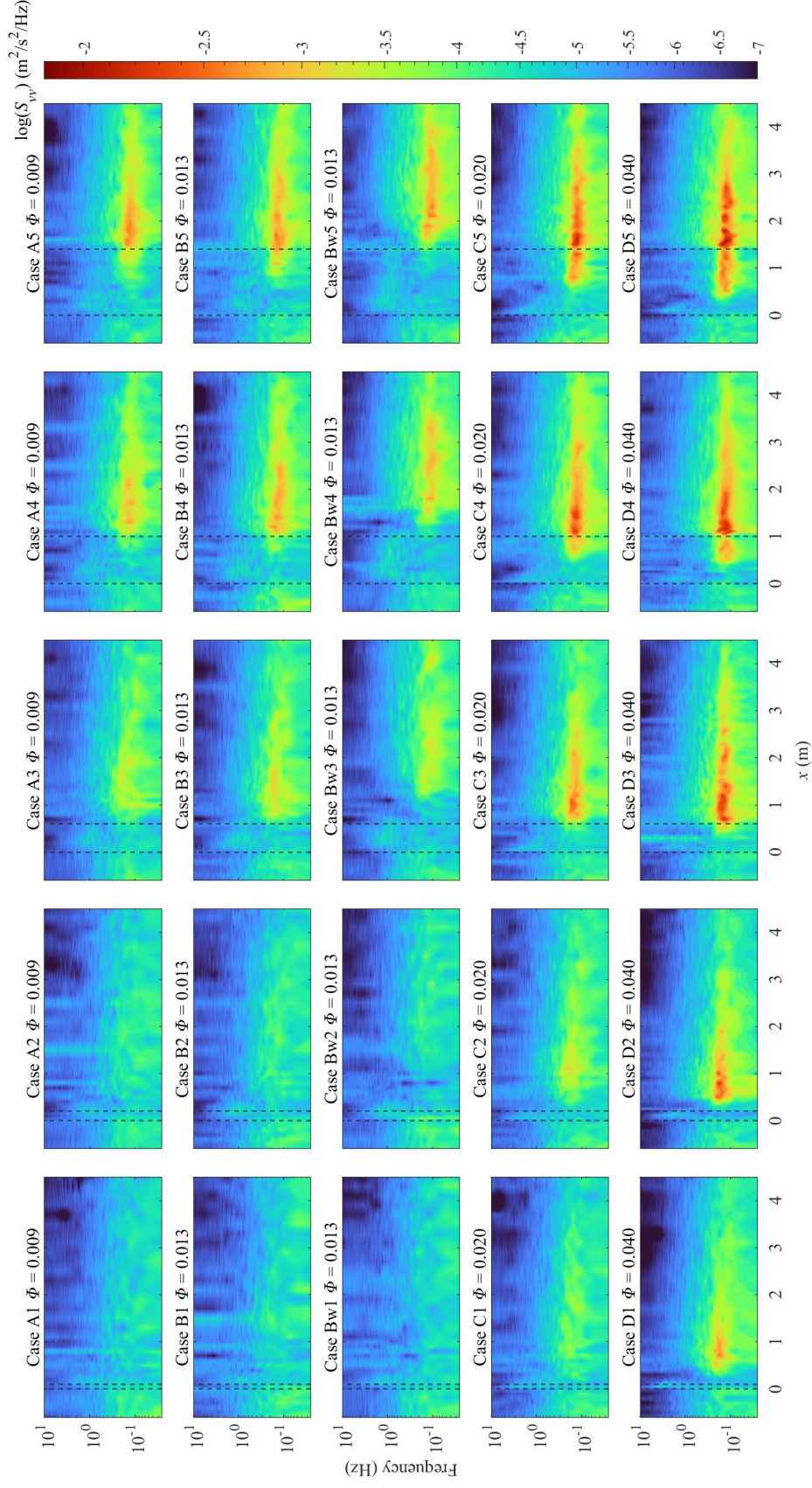


Figure 4.10: Power spectra  $(S_{vv})$  along the patch centerline ( $y = 0$ ). The dashed lines indicate the leading edge and trailing edge of the patch. Note: the width ( $W$ ) of Cases Bw = 0.21 m, Cases A  $\sim$  D = 0.09 m.

In contrast, the increasing patch density could locally enhance the drag force and dispersive stress on the local flow.

Beyond the trailing edge, a steady wake region can be raised for short and sparse patches, where momentum transport is dominated by advection effect (Zong & Nepf 2012, Kim et al. 2018). The steady wake length ( $L_1$ ) would be shortened with an early onset of vortex street. Wake vortex street can be found directly downstream of the patch (i.e.,  $L_1 = 0$ ) when  $L > L_i$  under large  $\Phi$  (e.g., Case D3), or large  $L/W$  (e.g., Cases A4, A5, B4, B5) or a combination of  $\Phi$  and  $L/W$  (e.g., Cases C3, D4, D5). According to Figure 4.11a, 4.11b and Table 4.2, both  $U_1/U_\infty$  and  $L_1/W$  decrease as  $\Phi$  increases within uncertainty. For Cases A ( $\Phi = 0.009$ ), both  $U_1/U_\infty$  and  $L_1/W$  show a continuous decrease trend as  $L/W$  increases, while  $U_1/U_\infty$  presents a recovery trend for other cases with higher density ( $\Phi > 0.009$ , i.e., Cases B, C, D). The unsteady wake length ( $L_2$ ) is dependent on both the velocity recovery rate,  $(U_\infty - U_1)/L_2$ , and initial velocity deficit,  $(1 - U_1/U_\infty)$ , at the wake vortex initiation point. The velocity recovery rate describes the rate of momentum input outside the wake while the initial velocity deficit describes the momentum required for full recovery. However, these two factors are interdependent and further complicate this issue. The unequal contributions of turbulence and velocity difference lead to a non-monotonic trend of  $L_2$  to  $\Phi$  and  $L/W$ . Regarding the influence of the patch width, Cases Bw with a width of 0.21 m present larger  $L_1$  and  $L_2$ , smaller velocity difference as well as recovery rate compared to Cases B with a width of 0.09 m, indicating that patch width may have a negative effect on the generation of a vortex street. From the aspect ratio perspective, widening the patch performs like shortening the patch. However, only two patch widths are examined here (not shown in the figure), further investigation with varying patch widths is recommended to confirm this finding.

#### 4.4.2 Coexistence between KH vortex street and wake vortex street

According to the observations in the current experiment (Figure 4.10) and previous studies (Rominger & Nepf 2011), two parallel KH vortex streets tend to be triggered due to flow instability along the lateral interfaces. Therefore, it is of great interest the correlation between the KH vortex streets and the wake vortex streets. A straight-forward way is to use dye tracer to track the vortex evolution, for example, releasing dye tracers simultaneously along the patch edge and at the wake. However, this method is not effective due to the strong dispersion of dye tracers within water flows. Alternatively, the frequency of the two kinds of vortices may be another indicator to imply their connection.

Similar to the Karman vortex description, the presence of KH vortex can be determined through the velocity power spectra ( $S_{vv}$ ) distribution along the patch lateral edge ( $x = 0 \sim L$ ,  $y = W/2$ , Figure 4.12). The dashed lines in the figures indicate their perspective interior adjustment length ( $L_i$ ). As shown in Figure 4.12, a peak in  $S_{vv}$  distribution demonstrates the initiation of

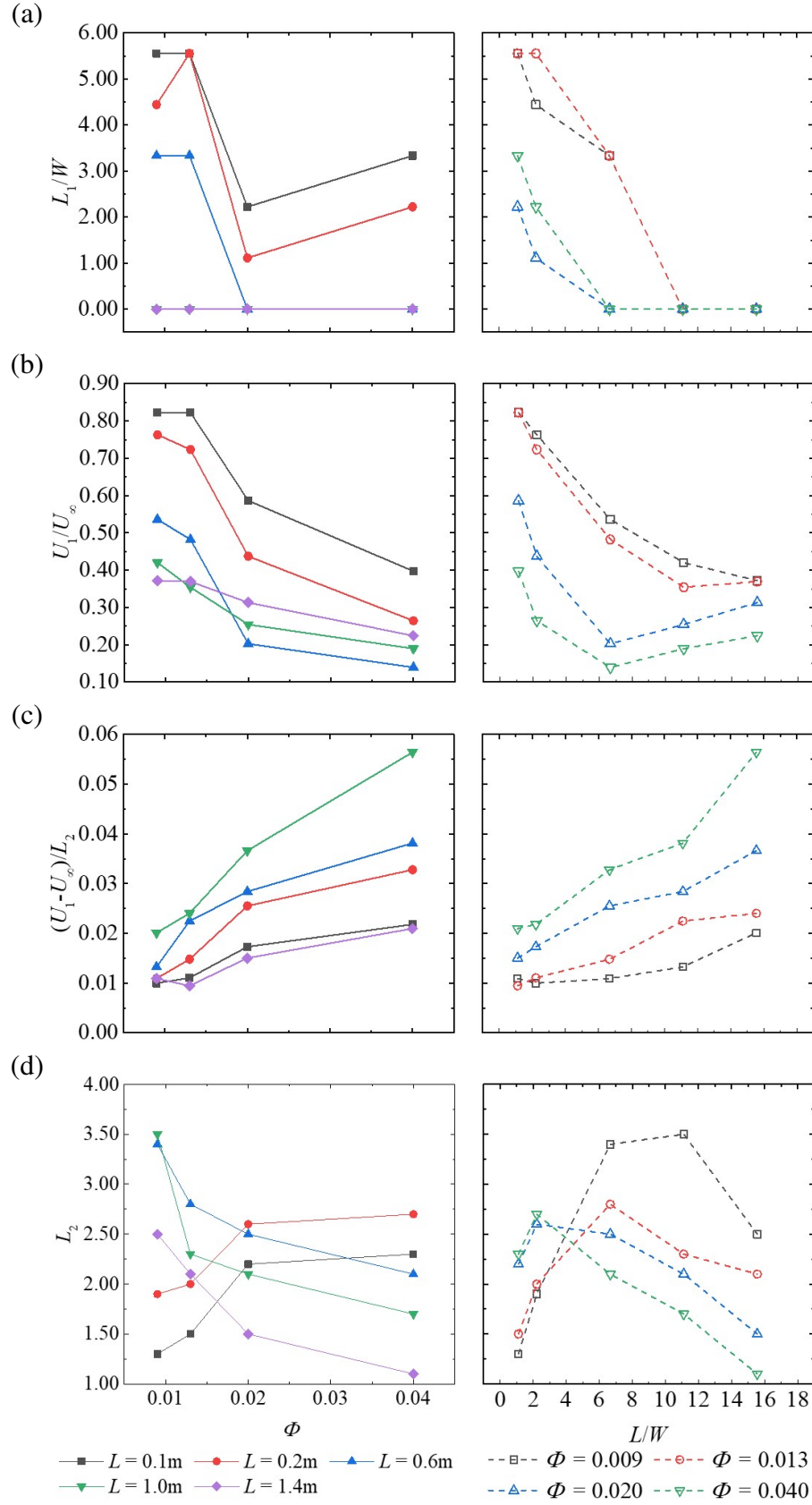


Figure 4.11: The impact of  $\Phi$  (left) and aspect ratio ( $L/W$ , right) on (a) normalized steady wake length,  $L_1/W$ , (b) normalized steady wake velocity,  $U_1/U_\infty$ , (c) wake recovery rate,  $(U_\infty - U_1)/L_2$ , (d) wake recovery length,  $L_2$ .

KH vortex (White & Nepf 2007, Caroppi et al. 2020, Proust & Nikora 2020, Yan, Duan, Wai, Li & Wang 2022). Specifically, when approaching  $L_i$ , instability structure starts to form (indicated by yellow in Figure 4.12). Then, over  $L_i$ , KH vortex streets can be observed (indicated by red in Figure 4.12), which is consistent with the study of Rominger & Nepf (2011). As the flow travels downstream, the enhanced velocity gradient at the patch lateral edge and weakened flow diversion contribute to the generation of KH vortex street. This evolution will be intensified through the momentum exchange between the parallel KH vortex streets across the patch width (Rominger & Nepf 2011), given by the stronger peaks at Cases B ( $W = 0.09$  m) relative to Cases Bw ( $W = 0.21$  m). Moreover, the presence of these peaks also complies with the occurrence of in-patch peaks (Figure 4.10). Therefore, the Karman-like structure within the patch is proved to be a result of the interaction of the two parallel KH vortex streets. This in-patch Karman-like structure will persist after the patch as a Karman vortex street. Based on the analysis of the results presented in Figure 4.13, when KH vortex occurs, a peak presents at  $f_{KH} = 0.12 \sim 0.17$  Hz in  $S_{vv}$ , with an average of 0.14 Hz, consistent with the mean value of  $f_{VK} = 0.15$  Hz for patch-scale Karman vortex street, indicating that KH vortex does have some similarity with Karman vortex.

Furthermore, the results of the normalized Reynolds shear stress at  $x = L$ ,  $y = W/2$  for all cases are shown in Figure 4.14. The normalized shear Reynolds stress at the end of trailing edge shows an increasing trend as aspect ratio and solid volume fraction increase, indicating the formation and growth of the KH vortex. This result is consistent with the peak values presented in the velocity power spectra above. However, when the length of Case D ( $\Phi = 0.040$ ) extends from  $L = 1.0$  m to  $1.4$  m, a sudden drop occurs, which is mainly caused by the strong interaction between two KH coherent structures developed along the parallel edges of the patch. This interaction leads to the formation of an in-patch Karman-like vortex, which results in vortex intensity dissipation and velocity recovery as indicated in Figure 4.4 and Figure 4.5. This Karman-like vortex has also been observed in the study of cylinders in tandem (Hosseini et al. 2020). Moreover, this in-patch Karman-like structure may explain why natural patches may not keep elongating downstream unrestrictedly but present an equilibrium length. Meanwhile, there exists a threshold value for normalized Reynolds shear stress,  $-\overline{u'v'}/u_*^2$  (shown by the dashed line in Figure 4.14), indicating the presence of KH vortex street. More importantly, according to Figure 4.14, a Karman vortex will be certainly detected if KH vortex presents, but Karman vortex can also form with the absence of KH vortex. Therefore, here we consider that KH vortex is a positive but not necessary condition for Karman vortex initiation.

#### 4.4.3 Wake vortex street formation thresholds

The generation of wake vortex street may significantly impact the flow velocity distribution, scalar convection and dispersion, sediment deposition and morphodynamics in the wake (Follett



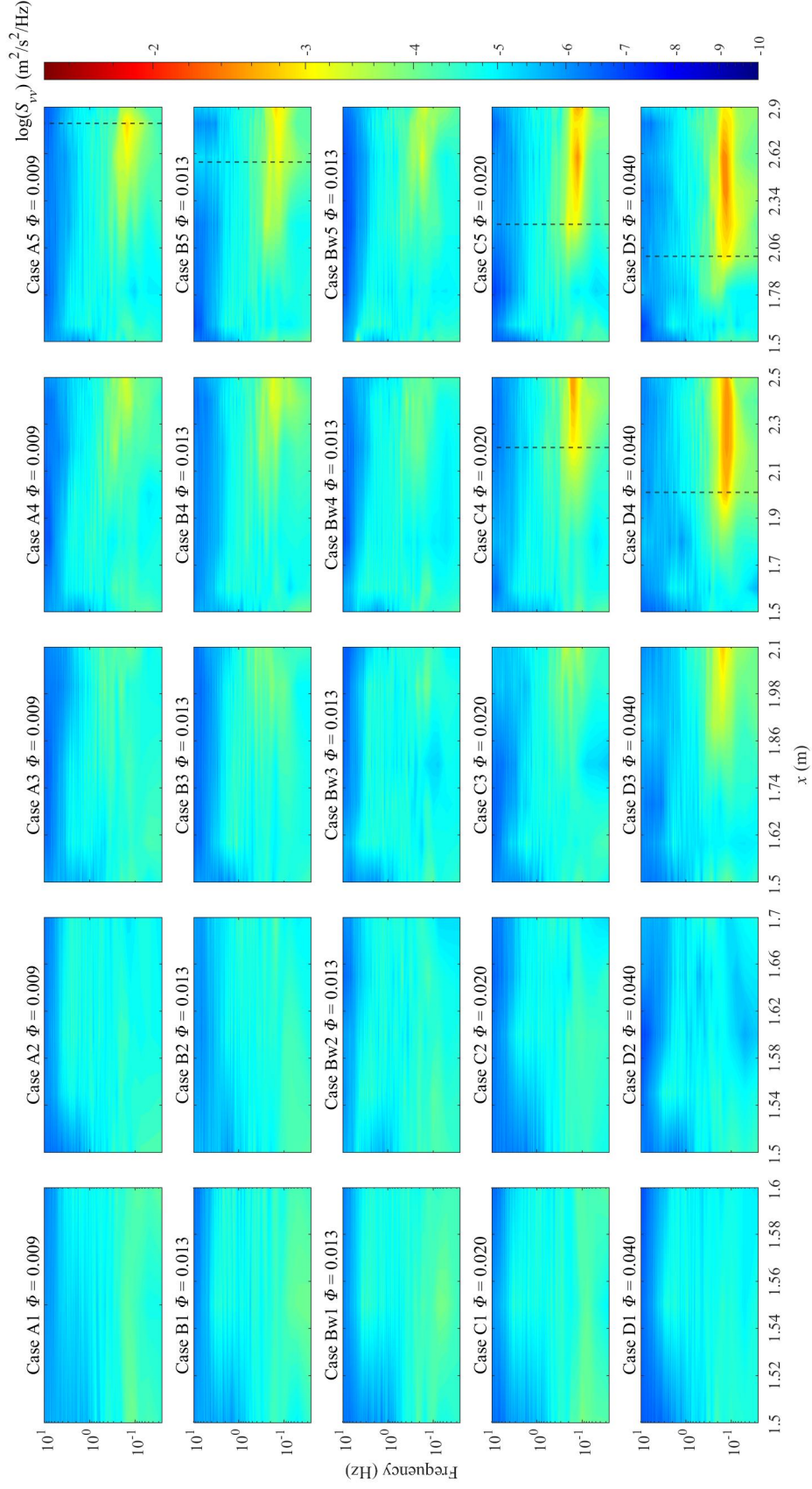


Figure 4.12: Power spectra ( $S_{vv}$ ) along the lateral edge of the patch ( $x = 0 \sim L, y = W/2$ ). The dashed lines indicate the interior adjustment region ( $L_i$ ). Note: the width ( $W$ ) of Cases Bw = 0.21 m, Cases A  $\sim D$  = 0.09 m.

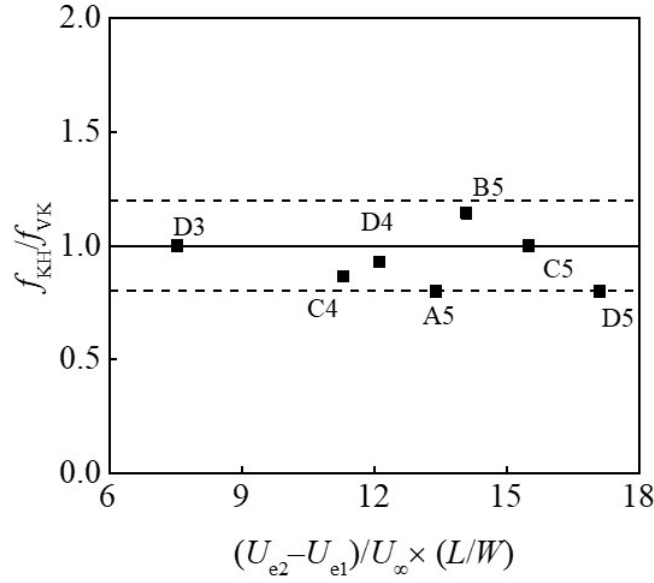


Figure 4.13: Comparison between  $f_{VK}$  and  $f_{KH}$ .  $f_{VK}$  is the frequency of von Karman vortex and  $f_{KH}$  is the frequency of KH instability. Both are measured from velocity power spectra. The solid line indicates  $f_{VK} = f_{KH}$  and the dashed lines indicates the 80% confidence intervals.

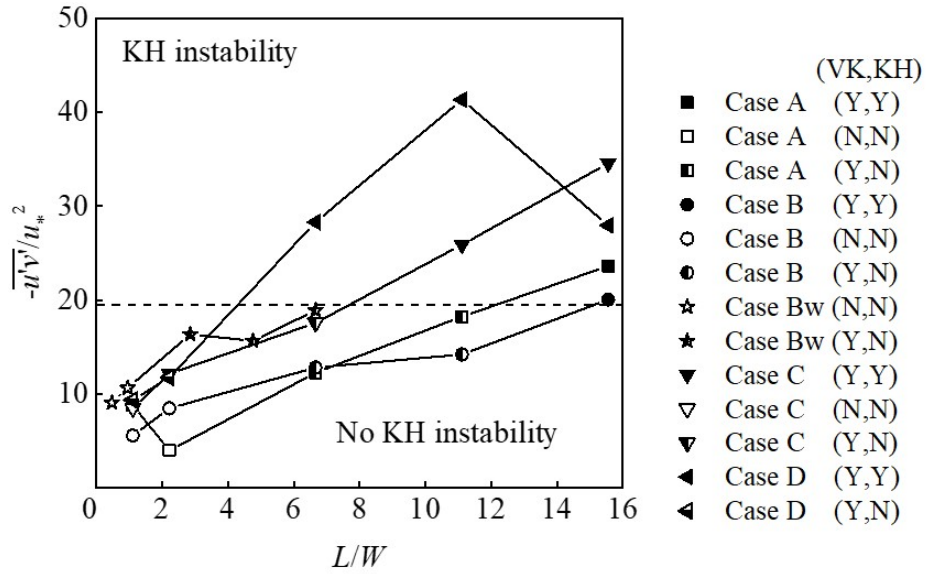


Figure 4.14: Normalized Reynolds stress at the position of  $(x, y) = (L, W/2)$ . The dashed line indicates the threshold value for normalized Reynolds stress of the presence of KH vortex. “VK” indicates wake vortex street; “KH” indicates KH vortex street; “Y” indicates yes/presence; “N” indicates no/absence.



& Nepf 2012, Zong & Nepf 2012, Liu et al. 2018). Therefore, a threshold indicator of wake vortex street is desirable. Considering the available implementations for different scenarios, three groups of threshold parameters are identified based on the results and findings above.

It has been noted that the initiation and growth of large-scale coherent structures are related to the velocity asymmetry imposed by factors such as, the topographic forcing in the transition region of the compound channel (Dupuis et al. 2017, Proust et al. 2017), and multilayered density stratification (Caulfield et al. 1995). Similarly, the cessation of the wake vortex street has been shown to be related to the velocity difference (or gradient) induced by the porous patch because a high-velocity bleed flow can prevent the shear layers developed along two sides to reach each other. Intuitively, the parameter combination of  $U_1$  and  $U_2$  (see definition in Figure 4.1) at the wake vortex onset location is available for the threshold identification following Zong & Nepf (2012). That is, when  $(U_2 - U_1)$  is too small, wake instability is unlikely to be triggered to form wake vortex streets. According to our experiments, a distinct vortex street appears when  $U_1/U_2 < 0.5$ , which is different from the result ( $U_1/U_2 < 0.35$ ) from experiments conducted by Zong & Nepf (2012) and numerical experiments by Chang & Constantinescu (2015) regarding a circular patch (i.e.,  $L/W = 1$ ).

In addition to vegetation density as stated in previous studies, the wake instability has been found to be related to the patch aspect ratio ( $L/W$ ) based on our experiments. Under the same density investigated in this chapter, the vortex generation is promoted by patch length ( $L$ ) and suppressed by patch width ( $W$ ). Therefore, an integrated nondimensional threshold value can be resulted as  $U_1/U_2 \times (L/W)^{-1}$ , which is more appropriate for the threshold identification. Therefore, a threshold map for the wake vortex generation can be formed as shown in Figure 4.15. Using a linear boundary  $U_1/U_2 \times (L/W)^{-1} = 0.31$ , no vortex street within the shaded area and vortex street can be well identified within the non-shaded area (Figure 4.15a). This threshold incorporating the effect of the aspect ratio can express well the results of existing works (Zong & Nepf 2012) that are special cases of this expression. Alternatively, we can also use  $(U_2 - U_1)/U_\infty$  to represent the normalized velocity difference (Figure 4.15b). In this case, the nondimensional parameter is defined as  $(U_2 - U_1)/U_\infty \times L/W$  and it shifts to 0.84. That is, vortex street occurs when  $(U_2 - U_1)/U_\infty \times L/W > 0.84$ .

Although the impact of patch length on velocity adjustment has been considered in  $U_1$ ,  $L$  incorporated here is a consideration for the impact of KH instability rather than normalization purpose. Under a low-density patch with sufficient length, the reduced velocity within the patch enhances the lateral velocity gradient as traveling downstream. This strengthened velocity gradient may trigger the presence of KH instability. Before the generation of an in-patch Karman-like vortex due to the interaction of the KH vortex, the formed KH instability has positive effects on the wake vortex street formation as well. For example, Case C1 presented a close but slightly higher velocity gradient ( $(U_2 - U_1)/U_\infty/W = 5.6 \text{ m}^{-1}$ ) than that in Case Bw4

(( $U_2 - U_1$ )/ $U_\infty/W = 4.7 \text{ m}^{-1}$ ), but wake vortex presents after Case Bw4 rather than Case C1. It is possibly caused by the energy contributed by KH instability formed along the patch lateral edges in Case Bw4, indicated by the yellow in Figure 4.12, even though it is weak. In addition, in the last case in the experiment of Zong & Nepf (2012), with ( $U_2 - U_1$ )/ $U_\infty/W = 4.3 \text{ m}^{-1}$  (where  $D = 0.12 \text{ m}$  is the  $W$  in this case), no wake vortex occurs, though its velocity gradient is higher than that of the vortex-generated Case Bw3 (( $U_2 - U_1$ )/ $U_\infty/W = 3.6 \text{ m}^{-1}$ ) in our experiment. Thus, the length of the patch should be incorporated into the threshold indicator to consider the positive contribution from the KH instability.

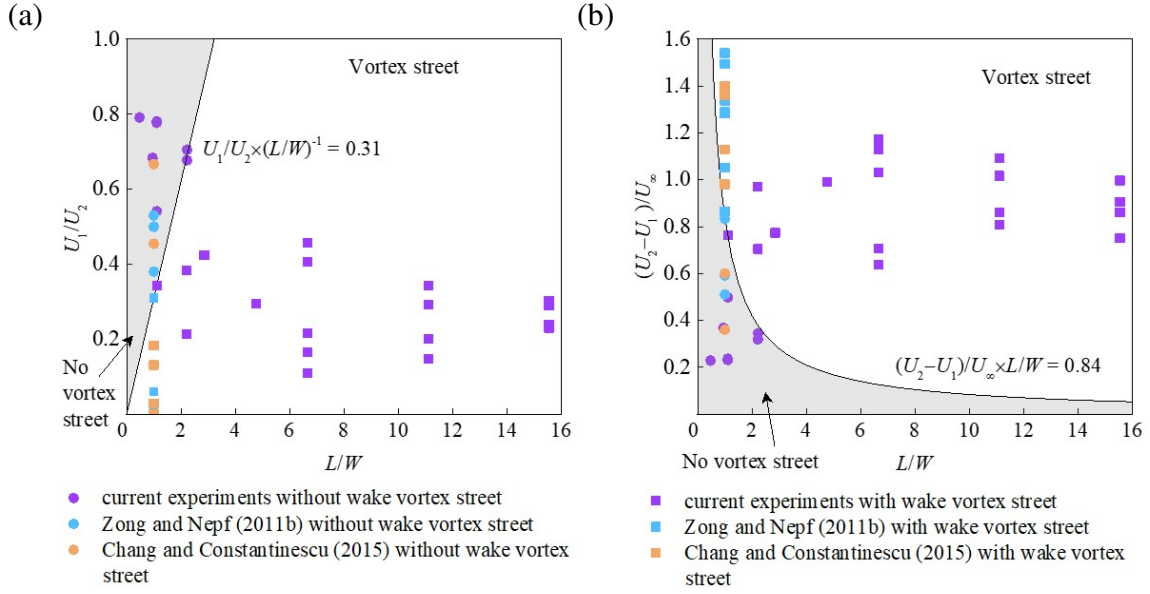


Figure 4.15: Velocity difference (a)  $U_1/U_2$ ; (b)  $(U_2 - U_1)/U_\infty$  at  $x = L + L_1$  versus aspect ratio ( $L/W$ ). The shaded area indicates the absence of wake vortex street according to the threshold value.

From a viewpoint of practical implementation, the sampling of  $U_{e1}$  and  $U_{e2}$  at the cross-section of the trailing edge ( $x = L$ ) is much easier compared with  $U_1$  and  $U_2$  by locating the onset of vortex initiation ( $x = L + L_1$ ). Chen, Ortiz, Zong & Nepf (2012) demonstrated that there existed some relationship between  $U_1$  and  $U_{e1}$ . In this sense, we also seek another threshold in the form of  $U_{e1}$  and  $U_{e2}$ . Similar to the above manipulation, a threshold map can be established for wake vortex street prediction as shown in Figure 4.16. The map implies that the vortex street forms at  $U_{e1}/U_{e2} \times (L/W)^{-1} < 0.35$  (except for Case D1) or  $(U_{e2} - U_{e1})/U_\infty \times L/W > 0.55$ .

Previous studies have reported that the solid volume fraction ( $\Phi$ ) of the porous obstacle can also be a simple indicator for vortex street generation. According to the study of Castro (1971), the vortex street ceases to form after a slim perforated plate ( $L/W \ll 1$ ) when  $\Phi < 0.8$ . For a circular porous array ( $L/W = 1$ ), Zong & Nepf (2012) reported that the cessation occurs at  $\Phi < 0.04$ , which is very close to the limit ( $\Phi < 0.05$ ) found in the numerical modeling by Nicolle

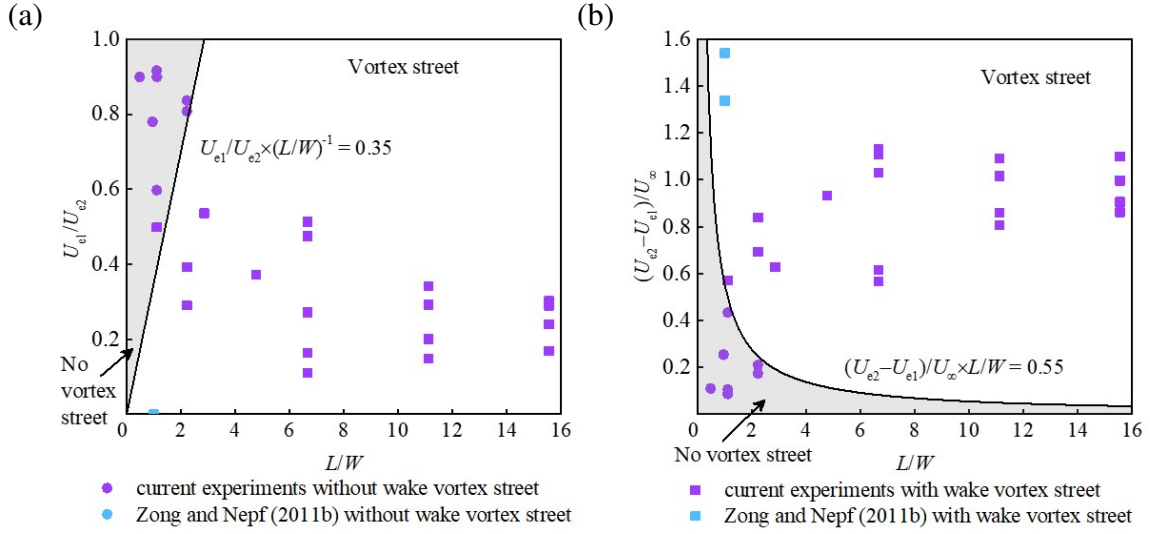


Figure 4.16: Velocity difference (a)  $U_{e1}/U_{e2}$ ; (b)  $(U_{e2} - U_{e1})/U_{\infty}$  at  $x = L$  versus aspect ratio ( $L/W$ ). The shaded area indicates the absence of wake vortex street according to the threshold value.

& Eames (2011). The inconsistent observations are due to the overlook of the impact of aspect ratios. Smaller aspect ratio leads to higher critical value. This is because  $\Phi$  only considers the local hydraulic resistance while the patch dimensions consider the reach of the hydraulic resistance. Considering the cumulative effect of patch dimensions, patch aspect ratio,  $L/W$ , is incorporated to be  $\Phi \times L/W$ . In the present experiments, increasing cumulative hydraulic resistance (by  $\Phi$  or  $L/W$ ), through altering the velocity shear in the wake, could play critical roles in promoting the formation of wake vortex streets.

When the patch of rigid emergent cylinders in aligned rectangular configurations with comparable streamwise and spanwise length scales (Cases A1  $\sim$  D1, with  $L = 0.10$  m and  $W = 0.09$  m,  $L/W = 1.11$ ), the transition occurs at  $\Phi = 0.020 \sim 0.040$ , which is close but slightly smaller than the ones observed in Nicolle & Eames (2011) and Zong & Nepf (2012). When patch elongates downstream, the transition occurs at  $\Phi = 0.013 \sim 0.020$  for cases with  $L/W = 2.22$ , which complies with our inference herein. Moreover, for  $L/W > 2.22$ , threshold values for  $\Phi$  are less than 0.009. Therefore, another threshold map ( $\Phi \times L/W > 0.045$ ) considering the cumulative resistance caused by  $\Phi$  and  $L/W$  is established for wake vortex street prediction as shown in Figure 4.17. However, this threshold will cease to hold true when  $\Phi$  is so low that velocity recovers before the end of the patch, which is not considered in this chapter. Therefore, the validity of this threshold map may be limited to a certain range of patch density and dimensions, which needs a broader-range investigation. It is better to understand the wake structure together with the velocity gradient. Moreover, this threshold map was developed for a single rectangular vegetation patch of rigid emergent cylinders in an aligned configuration. Hydraulic

resistance is expected to be higher in staggered configurations with less flow through patches, resulting in the onset of vortex street for lower solid volume fractions. Besides, the flexibility, the submergence ratio and the presence of leaves in real plants are not considered either, further investigations are expected.

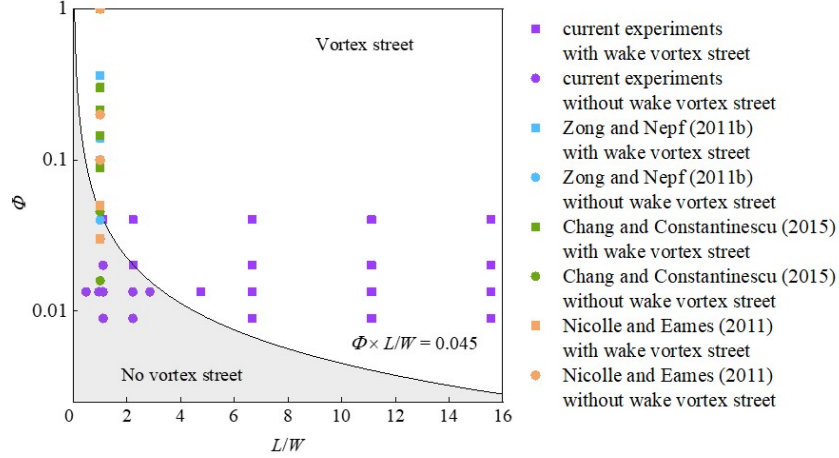


Figure 4.17: Aspect ratio ( $L/W$ ) versus solid volume fraction ( $\Phi$ ). The shaded area indicates the absence of vortex street according to the threshold value.

In consequence, three kinds of thresholds have been established for identifying the formation of wake vortex streets in a channel with vegetation patches of rigid emergent cylinders in an aligned configuration under different densities and aspect ratios, which can be used alternatively based on the availability of corresponding parameters in different scenarios.

(1) Quantified by velocity scales measured at the end of steady wake region ( $x = L + L_1$ ), Karman vortex street will appear when

$$U_1/U_2 \times (L/W)^{-1} < 0.31 \quad (4.1)$$

or

$$(U_2 - U_1)/U_\infty \times L/W > 0.84 \quad (4.2)$$

(2) Quantified by velocity scales measured at patch trailing edge ( $x = L$ ), Karman vortex street will appear when

$$U_{e1}/U_{e2} \times (L/W)^{-1} < 0.35 \quad (4.3)$$

or

$$(U_{e2} - U_{e1})/U_\infty \times L/W > 0.55 \quad (4.4)$$

(3) Quantified by patch characteristics, Karman vortex street will appear when

$$\Phi \times L/W > 0.045 \quad (4.5)$$

In this connection, this chapter forms an essential extension with substantial contribution to this scientific research. However, there still exists some limitations in this chapter. Firstly, only two widths were investigated in this case, the variation caused by varying patch widths and patch blockage ratios ( $W/B$ ) has not been systematically studied. Secondly, the influence of KH instability on wake structure has not been fully understood. An interesting future test would be expected to split the patch in half with a solid dividing barrier/plate along the patch centerline to prevent any lateral 'communication' of KH vortices across the patch (essentially forming two independent shear layers and weaker intensity) and see how it would affect KH vortex formation, especially for narrow cases. Thirdly, the combined impact of vegetation density ( $\Phi$ ) and patch aspect ratio ( $L/W$ ) was investigated under aligned configuration of rigid and emergent stems with uniform cylinder rods in this experiment. Hydraulic resistance is expected to vary under different configurations. Lastly, in natural system, the configuration will be even more complicated, features may evolve over time and space, with random configuration, irregular patch shape, and a wider range of stem sizes and densities. For instance, the threshold developed in this chapter failed to predict the formation of wake vortex after the natural, submerged patch with flexible leaves investigated in the field study of Biggs et al. (2019). This may attribute to the restriction of this threshold to rigid, emergent vegetation patches with no leaves or the limited measured reach in their study (Biggs et al. 2019). Therefore, the flexibility, the submergence ratio, the presence of leaves in real plants, and the varying flow conditions, such as incoming velocity and water depth, in natural aquatic systems need further systematically investigated.

## 4.5 Summary

This chapter experimentally addressed the importance of both solid volume fraction ( $\Phi$ ) and aspect ratio (length/width,  $L/W$ ) to the hydrodynamic behavior, particularly wake formation and structure, in response to a center-channel porous rectangular patch under aligned configuration of rigid and emergent stems. A total of 25 experimental runs under varying  $\Phi$  and  $L/W$  were carefully designed and carried out for investigation, with aid of rigorous velocity measurements and dye visualizations. The experimental results firmly demonstrated the significant impact of the patch aspect ratio on wake structure, complements previous experimental works on wake structures behind circular porous patches with comparable longitudinal and transverse dimensions.

It is observed that the solid volume fraction indicates the local hydraulic resistance, of which influence can be immediately felt by the local velocity adjustment, shown as the velocity gradient. Larger solid volume fraction leads to a faster velocity drop. However, patch dimensions

determine the reach of the resistance. Larger patch width delays the flow diversion laterally, leading to an adverse effect on the interior velocity adjustment, while the patch length controls the distance of the velocity drop and triggers the generation of KH instability along the patch lateral edges. Therefore, larger patch length and vegetation density may lead to higher velocity reduction but patch width presents the opposite impact. The combined effect of solid volume fraction and patch aspect ratio is representative of cumulative hydraulic resistance. It affects the wake structure by changing the bleed flow velocity and initiating KH instability at the patch trailing edge. Moreover, the two parallel KH vortex streets formed along the lateral edges of the patch under sufficiently high aspect ratios tend to interact with each other, leading to velocity recovery owing to transverse momentum input, especially for a smaller width. In contrast to the scenarios of high  $\Phi$  producing wake flow instability due to inducing large transverse velocity difference, the patch elongation through triggering KH vortex streets may impose an extra impact on the patch wake vortex street structures.

Furthermore, we attempted to explore the threshold for the generation of wake vortex streets based on previous and current observations. Three nondimensional-parameter-based threshold maps considering different indicator combinations were established. Based on the characteristic velocity scales ( $U_1$  and  $U_2$ ) at the onset location of vortex street ( $x = L + L_1$ ), wake vortex street would appear when  $U_1/U_2 \times (L/W)^{-1} < 0.31$  or  $(U_2 - U_1)/U_\infty \times L/W > 0.84$ . Based on the characteristic velocity scales ( $U_{e1}$  and  $U_{e2}$ ) at the trailing edge of the patch ( $x = L$ ), wake vortex street would occur when  $U_{e1}/U_{e2} \times (L/W)^{-1} < 0.35$  or  $(U_{e2} - U_{e1})/U_\infty \times L/W > 0.55$ . In addition, based on solid volume fraction ( $\Phi$ ) and aspect ratio ( $L/W$ ), wake vortex street will occur when  $\Phi \times L/W > 0.045$ . These three threshold maps can be alternatively used for theoretical interpretation and implementation by considering the parameter availability under different test scenarios. The first two threshold maps are likely to be applied to a wider range of patch configurations (and potentially also to flexible vegetation) since they are based on characteristic velocity scales in the wake. Further work is needed to determine whether the third threshold map based on solid volume fraction applies more broadly, since stem alignment, flexibility, and surface area (skin friction) may also be important factors leading to patch hydraulic resistance, velocity gradients, and vortex street formation.

# Chapter 5

## The influence of patch-edge vortices on wake dynamics

### 5.1 Introduction

Chapter 4 demonstrated that patch elongation enhances the velocity gradient along the side edges of a finite vegetation patch. This increased gradient promotes the formation of Kelvin-Helmholtz (KH) vortices at the patch edges and von Karman (VK) vortices in the patch wake. In addition to the velocity gradient, the wake structure is also influenced by the initiation of KH vortices. Notably, the simultaneous emergence of both patch-edge KH vortices and patch-wake VK vortices around an elongated rectangular patch suggests that these two vortex patterns tend to evolve at the same frequency (Figure 4.13). However, the findings in Chapter 4 are insufficient to fully characterize the initiation and evolution of along-edge KH vortices and their influence on wake flows. Consequently, this Chapter aims to further extend Chapter 4 by quantifying the impact of patch-edge KH vortices on the patch-wake structure. The main objectives of this chapter are:

- (1) to investigate the relationship between the cumulative hydraulic resistance and the velocity adjustment at the end of the patch;
- (2) to characterize patch-edge KH vortex at a patch with finite width and length and to quantify its effect on the patch-wake structure.

### 5.2 Materials and Methods

To further investigate the initiation and evolution of KH vortices at the side edges of elongated patches and their subsequent effects on wake structure, this chapter builds upon the work presented in Chapter 4. A broader range of patch lengths ( $L = 0.1 - 2.0$  m), and densities ( $\Phi = 0.007 - 0.080$ , corresponding to a frontal area per unit volume of  $a = Nd = 2.8 \sim 31.9\text{m}^{-1}$ )

was considered to generate a wider variety of wake patterns under comparable conditions. In total, 46 patch configurations were tested and analyzed, in addition to 19 experimental runs from Chapter 4. Detailed information for each case is provided in the Appendix A.

Data collection, data treatment, experimental setup and parameter definitions remain consistent with those used in Chapter 4.

## 5.3 Results and Discussions

### 5.3.1 Bleed flow deficit related to cumulative hydraulic resistance

Threshold values related to bleed flow deficit,  $(L/W)(U_{e2} - U_{e1})/U_\infty$ , and patch cumulative hydraulic resistance,  $\Phi L/W$ , have been developed to predict the initiation of wake vortex in Chapter 4. Specially, flow adjustment at the end of the patch is highly dependent on the patch cumulative hydraulic resistance, but  $(L/W)(U_{e2} - U_{e1})/U_\infty$  is not exactly equivalent to  $\Phi L/W$ , with different performances under the variation of patch density and aspect ratio. Under the same aspect ratio (Figure 5.1a), the bleed flow velocity deficit is initially positively associated with patch density and finally achieves equilibrium, implying full adjustment of the interior flow before the end of the patch. Increasing the patch density accelerates the interior flow adjustment, resulting in a shorter adjustment length. After the interior adjustment, the flow diversion diminishes, leading to a constant velocity difference at the end of the patch  $((U_{e2} - U_{e1})/U_\infty)$ , as indicated in Figure 5.1a. Therefore, it is assumed,

$$(U_{e2} - U_{e1})/U_\infty \propto (\Phi)^{-1}. \quad (5.1)$$

Under the same patch density and patch width that dominate the streamwise gradient of interior flow adjustment (Rominger & Nepf 2011, Zhang et al. 2023),  $(U_{e2} - U_{e1})/U_\infty$  is proportional to  $L/W$  before the full development of the flow within the patch, behaving like patch density (Figure 5.1b). Therefore,

$$(U_{e2} - U_{e1})/U_\infty \propto (L/W)^{-1}. \quad (5.2)$$

Here, considered that the bleed flow adjustment is a result of the combined contributions from patch density and aspect ratio, it is assumed,

$$(U_{e2} - U_{e1})/U_\infty = k - c_1/(\Phi L/W + c_2), \quad (5.3)$$

where  $k$ ,  $c_1$ ,  $c_2$  are scaling factors to meet the extreme conditions and ensure the equation's validity. For instance, for an extremely high-density porous patch like a solid obstruction or an elongated patch with an interior velocity decay to zero (Rominger & Nepf 2011),  $\Phi L/W \gg c_1$ ,  $U_{e1} \approx 0$  and  $U_{e2} \approx U_\infty$ , then  $(U_{e2} - U_{e1})/U_\infty = k = 1$ ; for an extremely low-density porous patch



like none of obstruction, i.e.,  $\Phi = 0$ ,  $U_{e2} - U_{e1} = 1 - c_1/c_2 = 0$ , thus  $c_1 = c_2$ . Then,

$$(U_{e2} - U_{e1})/U_\infty = 1 - c_1/(\Phi L/W + c_1). \quad (5.4)$$

By data fitting with all measured data, it is obtained,

$$(U_{e2} - U_{e1})/U_\infty = 1 - 0.03/(\Phi L/W + 0.03). \quad (5.5)$$

with a correlation coefficient equal to 0.75 ( $R^2 = 0.75$ ). Particularly, data related to circular patches (i.e.,  $L/W = 1$ ) (Chen, Ortiz, Zong & Nepf 2012) is also included in Figure 5.1c, demonstrating the generality of the developed formulation (i.e.,  $L/W = 1$ ). However, some deviations exist between the predicted and measured values, attributed to the blocking effect and the contribution from patch size on velocity adjustment. Further investigation is required to clarify the roles of these factors in flow adjustment.

To conclude, patch cumulative hydraulic resistance,  $\Phi L/W$ , promotes the velocity difference between the in-patch and lateral-outside-patch regions, until the interior flow fully develops. However, according to the observations in Chapter 4, in addition to velocity adjustment, patch dimensions should be incorporated (i.e.,  $(L/W)(U_{e2} - U_{e1})/U_\infty$ ) to include the impact of the presence of patch-scale KH vortex at the patch lateral edges on the wake structures.

### 5.3.2 Patch-edge KH coherent structure

In addition to the wake VK vortex, patch elongation actively contributes to the initiation of KH vortex at the patch lateral interfaces. The initiation and strength of the large-scale coherent structure is identified by the peak in power spectra density ( $S_{vv}$ ) and oscillations in the autocorrelation ( $R_{vv}$ ) of the cross-stream velocity series (Caroppi et al. 2019) collected at the end of the patch lateral edge ( $x = L$ ,  $y = W/2$ ). The frequency ( $f$ ) in  $S_{vv}$  is normalized by the local momentum thickness,  $\theta$ , and convection velocity,  $U_c$ , to be  $f\theta/U_c$ , where  $\theta = \int_{-\infty}^{+\infty} [1/4 - ((U - U_c)/\Delta U)^2] dy$ ,  $U_c = (U_{e2} + U_{e1})/2$  and  $\Delta U = U_{e2} - U_{e1}$ . The spectra manifest a clear peak approximately at  $f\theta/U_c = 0.032$ , which meets the natural frequency of KH vortices in a plane mixing layer and has been observed in shear layers in partly vegetated flows with both rigid cylinders (White & Nepf 2008) and flexible vegetation (Caroppi et al. 2019). The results obtained from  $S_{vv}$  is consistent with those in  $R_{vv}$  (Figure 5.2). Similar to the initiation of wake VK vortex (Zhang et al. 2023), the threshold value of  $L/W$  for the KH initiation will be lower under a higher  $\Phi$ . Besides, the growth and full development of the patch-edge KH vortex are indicated by an initial enhancement and a final equilibrium of the peaks or oscillations in Figure 5.2. The weak peaks and small oscillations indicate the generation of small-scale coherent structures in cases with a  $\Phi = 0.080$ , smaller than the patch-scale

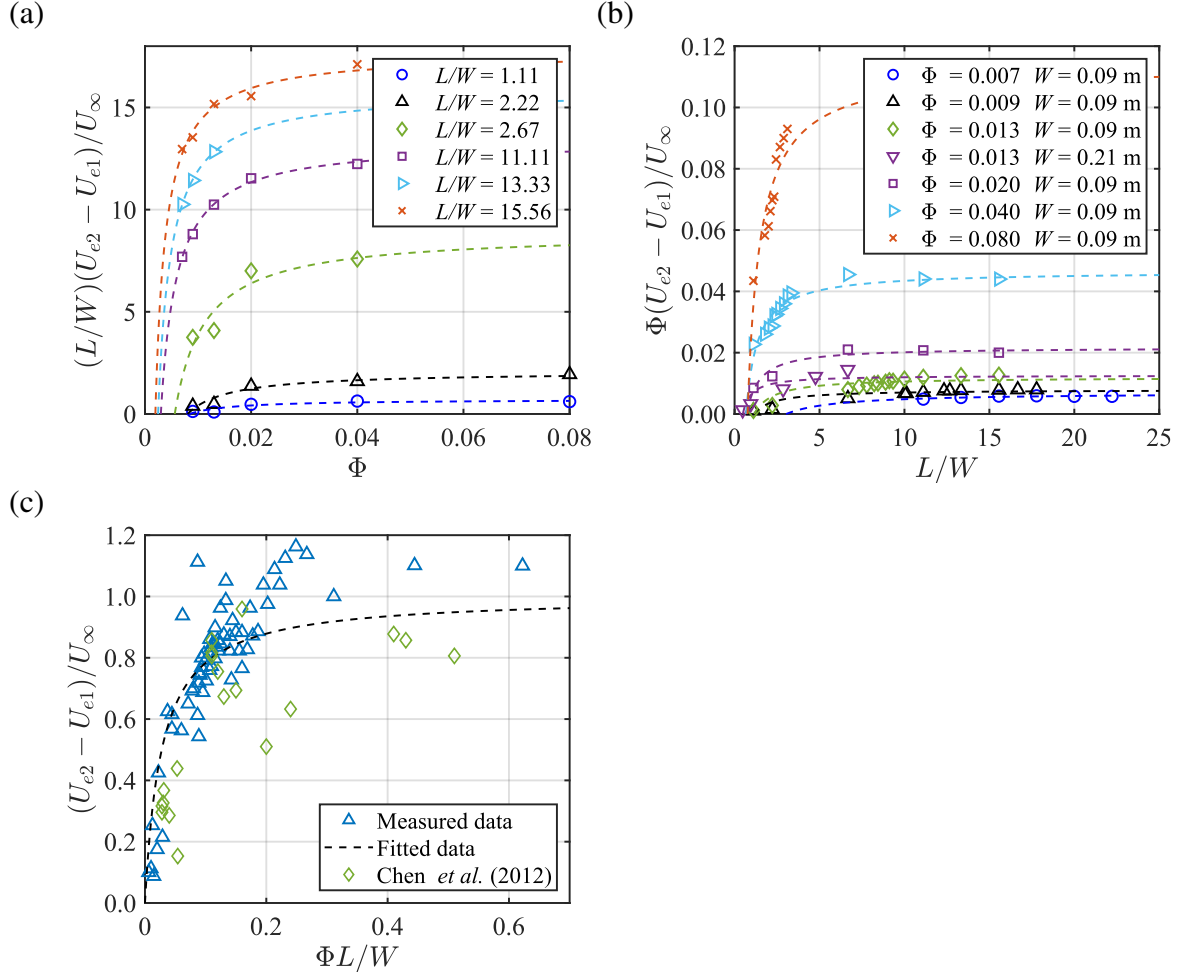


Figure 5.1: The relationship between the bleed flow adjustment,  $(U_{e2} - U_{e1})/U_{\infty}$ , and (a) patch density,  $\Phi$ , shifted by  $L/W$  for clarity; (b) patch aspect ratio,  $L/W$ , shifted by  $\Phi$  for clarity. The dashed lines with corresponding color for each case indicate the general trend of the measured data. (c) The relationship between  $(U_{e2} - U_{e1})/U_{\infty}$  and cumulative hydraulic resistance,  $\Phi L/W$ . The dashed line indicates Eq. 5.5, with a coefficient of determination,  $R^2 = 0.75$ .

coherent structures, which are not considered in the present work.

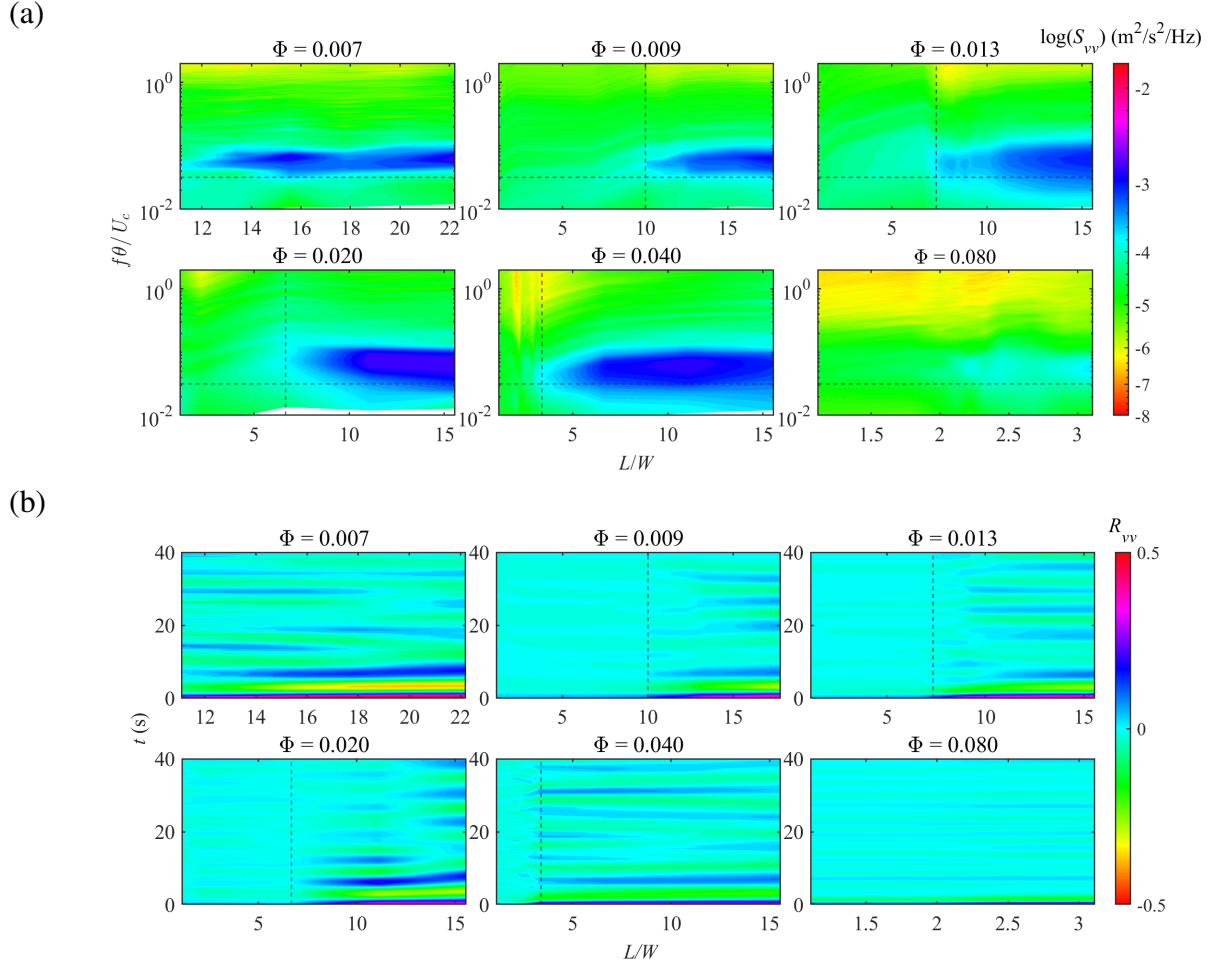


Figure 5.2: The initiation and evolution of the patch-scale KH vortex at the end of the patch side edge, i.e.,  $(x, y) = (L, W/2)$  at different values of  $L/W$  under varying  $\Phi$ , evaluated by the (a) power spectra density ( $S_{vv}$ ), with a horizontal dashed line indicating the natural frequency for a free shear layer,  $f\theta/U = 0.032$ ; and (b) autocorrelation ( $R_{vv}$ ) of the spanwise velocity. The vertical dashed line indicates the threshold value of  $L/W$  for the initiation of the patch-edge KH vortex.

However, another criterion related to velocity shear ( $\lambda$ -criterion) developed in compound channels or partly vegetated channels (Caroppi et al. 2019, Dupuis et al. 2023) fails to predict the formation of the patch-scale KH vortex at the patch end (Figure 5.3a). Relative to the vortex initiated at a single interface, the interaction of the two KH vortex streets at two parallel streamwise edges across the patch width ( $W$ ) should be considered in the in-stream located patches, since this communication may enhance the turbulence intensity of the KH vortices (Rominger & Nepf 2011). Besides, the  $\lambda$ -criterion was developed from the fully developed transect, but the in-patch flow is not always fully adjusted by the end of the patch investigated

in the present work, due to the limited streamwise dimensions. Before fully developed, the in-patch flow keeps diverting into the lateral bare regions, preventing the initiation of the patch-scale coherent structures at the lateral interfaces. For cases with high velocity difference, the patches with low density may have achieved fully developed while the high-density ones may still be in the interior adjustment process. Therefore, the aspect ratio ( $L/W$ ) is incorporated to consider the extra impacts imposed by the finite dimensions of the patches in the present work, including the interaction of two KH vortex streets across the patch width and the flow diversion due to interior flow adjustment. In Figure 5.3b, patch-edge KH vortex can be detected at the end of the patch when  $(L/W)(U_{e2} - U_{e1})/U_\infty > 4.8$ , and the turbulent intensity of the KH generally enhances as  $(L/W)(U_{e2} - U_{e1})/U_\infty$  increases. Although the magnitude of the velocity difference is relatively small compared to the aspect ratio under an elongated patch, velocity difference is essential in KH vortex generation. For instance, in the partly vegetated flow with sufficient streamwise length, vortex can be triggered once the velocity shear over the threshold value (Caroppi et al. 2019). In a circular or square patch with an aspect ratio = 1 (Chen, Ortiz, Zong & Nepf 2012),  $(U_{e2} - U_{e1})/U_\infty$  represents the overall effect of patch density and patch size. Although patch density is not directly presented in this parameter, the impact of which is incorporated in the velocity adjustment.

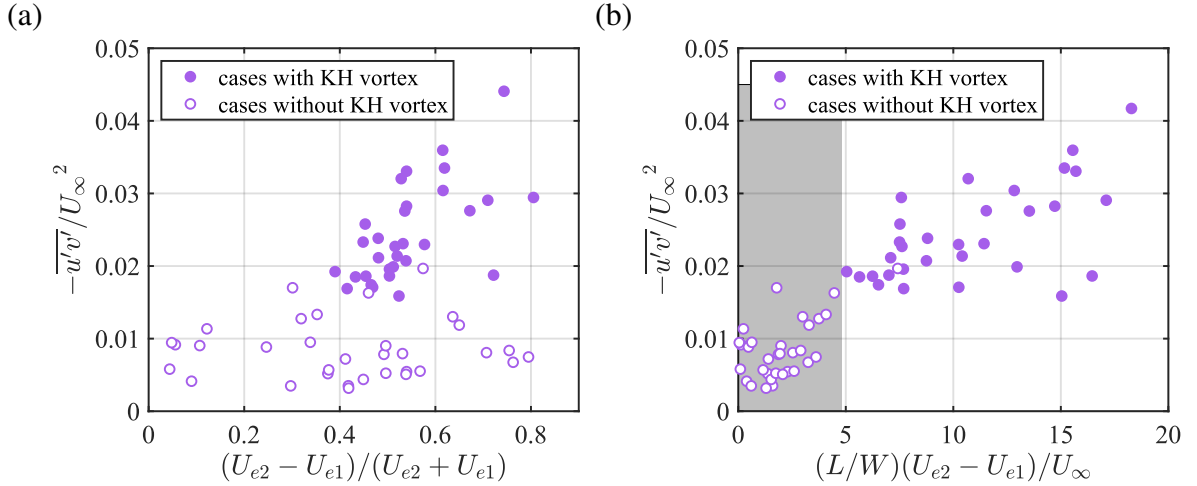


Figure 5.3: Indicator for the patch-edge KH vortex initiation and normalized Reynolds stress at the position of  $(x, y) = (L, W/2)$ : (a) velocity shear,  $(U_{e2} - U_{e1})/(U_{e2} + U_{e1})$ , and (b) velocity difference along with aspect ratio,  $(L/W)(U_{e2} - U_{e1})/U_\infty$ .

### 5.3.3 The contribution of the patch-edge KH vortex to wake structure

According to the velocities collected along the patch centreline ( $y = 0$ ), both normalized steady wake length ( $L_1/\sqrt{A}$ ) and steady wake velocity ( $U_1/U_\infty$ ) are suppressed as  $\Phi L/W$  increases (Figure 5.4a and 5.4b), where  $A$  refers to the area of the patch,  $A = LW$ .  $\sqrt{A}$  is used to represent

the overall size of the rectangular patch, similar to the role of the patch diameter ( $D = \sqrt{D^2}$ ) in the analysis of circular patches with an identical streamwise and spanwise dimension,  $L = W = D$  (Chen, Ortiz, Zong & Nepf 2012, Zong & Nepf 2012). The turbulence energy associated with patch-wake coherent structure,  $(U_2 - U_1)^2$ , is normalized by the energy associated with bed-friction turbulence,  $1/2(U_2 + U_1))^2$ . The normalized energy of the wake VK vortex is stronger after a patch with a larger value of  $\Phi L/W$  (Figure 5.4c). However, for circular patches with an aspect ratio = 1, the wake flow's behavior varies after patches with the same solid volume fraction but different diameters. The variation of the wake structures under the same value of  $\Phi L/W$  (Figure 5.4a – 5.4c) indicates the unequal contributions from  $\Phi$  and  $L/W$ .

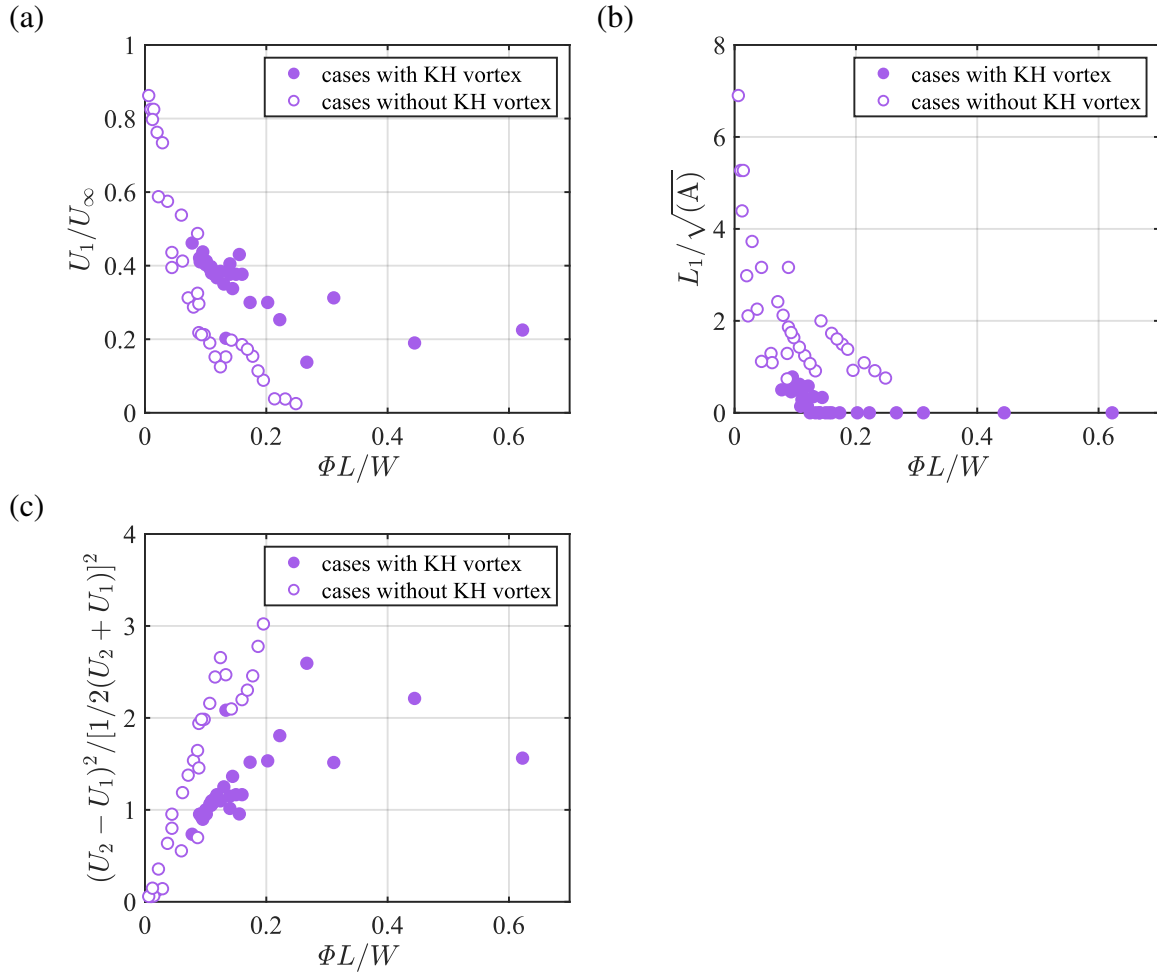


Figure 5.4: The impact of the patch's cumulative hydraulic resistance ( $\Phi L/W$ ) on (a) the normalized steady wake velocity,  $U_1/U_\infty$ , (b) the normalized steady wake length,  $L_1/\sqrt{A}$ , and (c) the normalized energy of the wake vortex,  $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ .

Patch aspect ratio affects the wake flow not only by adjusting the bleed flow velocity but also by triggering the KH initiation along the lateral edges, different from patch density. Thus, it is considered the variations in the wake flow performances are introduced by the presence of the

patch-edge KH vortex. However, the influences of bleed flow velocity adjustment and the patch-edge KH vortex generation cannot be simply evaluated by  $\Phi$  and  $L/W$  separately, since patch elongation also makes contributions to modify transverse velocity gradient. To obtain a better understanding of the impact from the initiation of the patch-edge KH vortex, wake structures are compared under the same normalized transverse velocity gradient obtained at the end of the patch,  $(U_{e2} - U_{e1})/U_{\infty}/(W/B)$ , with flume width,  $B$ , for normalization. Two distinct trends are detected in the wake structure, with a gap evaluating the contribution of the KH vortex (Figure 5.5a – 5.5c). Figure 5.5b directly manifests that the generation of the patch-edge KH vortex may decline the steady wake length, implying that the patch-edge KH vortex grows faster than the shear layer thus the mixing point will be closer to the patch trailing edge. Meanwhile, the steady wake velocities are enhanced compared to the patches without KH vortex (Figure 5.5a), revealing that the formation of patch-edge KH vortex may accelerate the velocity behind the patch. Furthermore, the normalized energy of the patch-wake VK vortex will be dampened when the upstream KH vortex is generated (Figure 5.5c). The enhancement or suppression (i.e., contribution) does not vary with the normalized transverse velocity gradient investigated. Therefore, the results suggest that the presence of the patch-edge KH vortex not only affects the flow condition at the patch lateral interfaces but also presents potential impacts on the wake structure or interacts with the wake vortex.

Indeed, the formation of the patch-scale KH vortex along the patch lateral interfaces induced by patch elongation may introduce extra influences on the wake flow. However, neither cumulative hydraulic resistance nor normalized transverse velocity gradient is a successful indicator for the wake structure since they cannot evaluate the patch-scale KH coherent structure. Given the fairly good performance of  $(L/W)(U_{e2} - U_{e1})/U_{\infty}$  in characterizing the initiation and evolution of the patch-edge KH vortex (Figure 5.3b), the wake structures can be well predicted by  $(L/W)(U_{e2} - U_{e1})/U_{\infty}$  (Figure 5.6a–5.6c). Before the patch-edge KH vortex initiates, i.e.,  $(L/W)(U_{e2} - U_{e1})/U_{\infty} < 4.8$ , the turbulent intensity is relatively low, thus the transverse velocity gradient dominates the wake structures. Under the above condition, the normalized steady wake length and normalized steady wake velocity drop while the energy of the wake Karman vortex enhances, as bleed flow velocity decays, consistent with the observations from circular patches with no patch-scale KH vortex formation (Zong & Nepf 2012). As  $(L/W)(U_{e2} - U_{e1})/U_{\infty}$  further increases, the patch-edge KH vortex starts to form and grow, disturbing the wake structures. This disturbance of KH vortex on wake flow is also discussed under a submerged circular patch (Liu et al. 2018). Although the wake structures behave differently before and after the patch-edge KH vortex occurs, they can be reasonably predicted by  $(L/W)(U_{e2} - U_{e1})/U_{\infty}$ , revealing the dominance of the combined effect of the transverse velocity gradient and the presence of KH vortex. Although  $\Phi$  is not directly presented in this parameter, its influences are incorporated in the velocity difference.

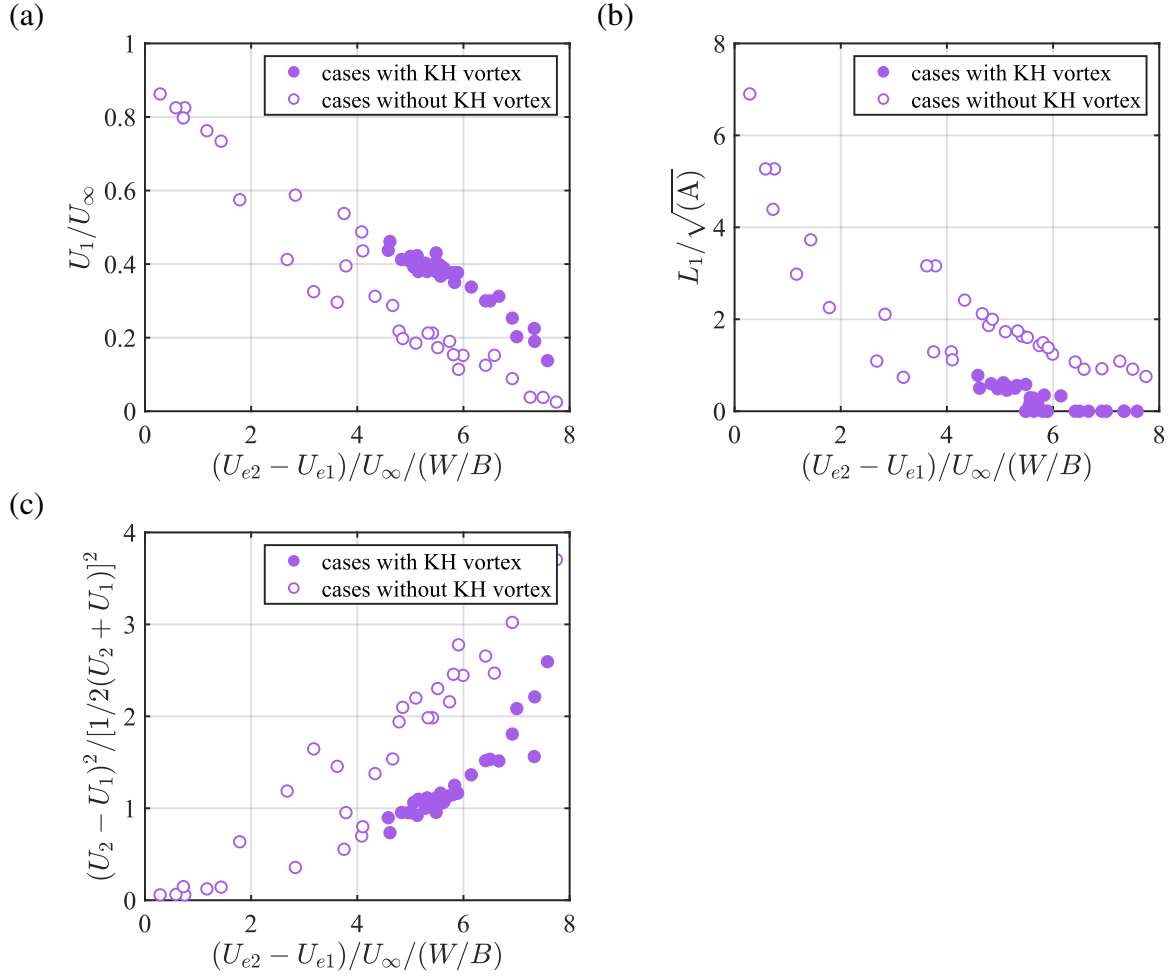


Figure 5.5: The impact of the lateral velocity gradient, normalized by channel width,  $(U_{e2} - U_{e1})/U_{\infty}/(W/B)$ , on (a) the normalized steady wake velocity,  $U_1/U_{\infty}$ , (b) the normalized steady wake length,  $L_1/\sqrt{A}$ , and (c) the normalized energy of the wake vortex,  $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ .

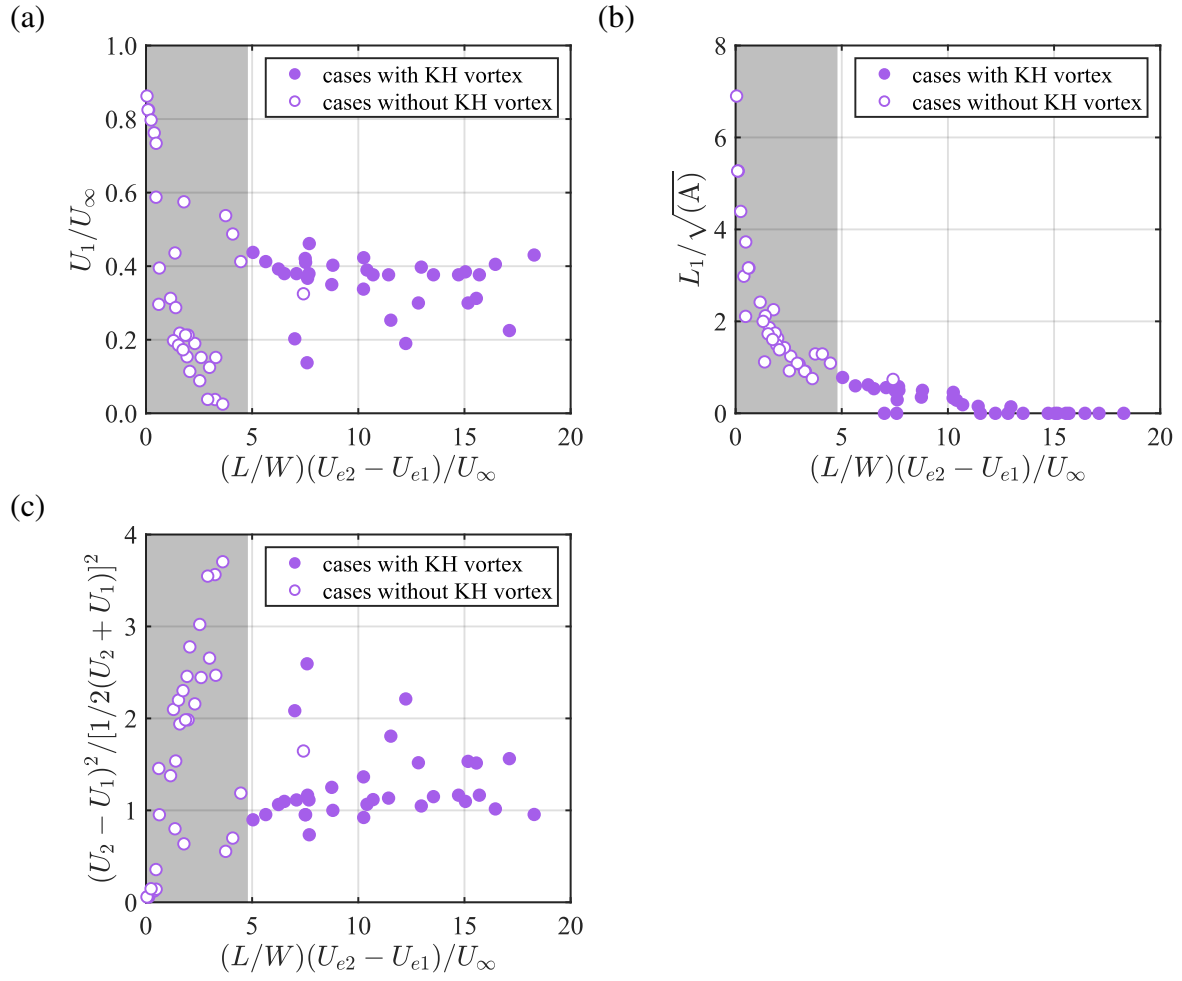


Figure 5.6: The impact of the patch-edge KH vortex on (a) the normalized steady wake velocity,  $U_1/U_{\infty}$ , (b) the normalized steady wake length,  $L_1/\sqrt{A}$ , and (c) the normalized energy of the wake vortex,  $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ .



Finally, a phenomenological model can shed light on the understanding of how the patch-wake VK vortex structure responds to the upstream patch-edge KH vortex. Without the KH vortex (e.g., short dense patch), two shear layers at the edge end ( $L, \pm W/2$ ) grow in parallel and then reattach to form VK vortex structure at the end of the steady wake zone (Zong & Nepf 2012). The self-rotation of the KH vortex structure with high turbulent energy tends to distort the two shear layers, leading to an asymmetrical oscillating steady wake (refer to Figure 5.3 in Zhang et al. (2023)). Furthermore, the fundamental properties of the wake structure are either enhanced (e.g.,  $U_1/U_\infty$ ) or weakened (e.g.,  $L_1/\sqrt{A}$  and  $(U_2 - U_1)^2/[1/2(U_2 + U_1)]^2$ ) by the KH vortex. Comparable phenomenon can be observed in the flow around two tandem square cylinders (Shui et al. 2021), where the upstream vortex contributes to suppressing the steady wake region after the downstream cylinder. This phenomenological model also offers some implications for the mathematical description of the co-existence of different vortex structures. Besides, the in-patch velocity recovery after the interior velocity adjustment (i.e., velocity drop) within a rectangular patch (Rominger & Nepf 2011, Zhang et al. 2023), can also prove the positive contributions from the KH vortex communication to steady wake velocity.

## 5.4 Summary

This Chapter investigates the relationship between the cumulative hydraulic resistance and bleed flow adjustment, and evaluates the responses of the wake structure to the formation of patch-scale KH vortices along the lateral interfaces of an in-stream located rectangular vegetation patch. By varying patch densities and aspect ratios, it is observed that patch elongation affects the wake structure by adjusting the bleed flow velocity deficit as well as triggering the KH vortex along the patch lateral edges. The initiation of the patch-edge KH vortex at a vegetation patch with finite length and width is highly sensitive to the aspect ratio of the patch, in addition to the velocity difference across the interface. Furthermore, the initiation of the patch-edge KH vortex may accelerate the steady wake velocity, shorten the steady wake length and decay the energy of the wake vortex. Finally, the wake structure can be quantitatively characterized by the combined effect of bleed flow velocity deficit and the initiation of the patch-edge KH vortex. This chapter improves the understanding of flow-vegetation dynamics and provides critical information on further studies on sediment transport, landscape evolution, and water quality management in vegetated streams, wetlands, estuaries and coastal regions.

# Chapter 6

## Development and interaction of Kelvin-Helmholtz vortices along two parallel fringing vegetation arrays

### 6.1 Introduction

In partially vegetated channels, a shear layer with regular vortex structures forms at the interface between the patch and adjacent open region (Caroppi et al. 2020, 2021) after flow deflection near the leading edge of the patch. These coherent vortices were triggered by Kelvin–Helmholtz instability initiated by the strong shear and velocity inflection at the array interface (Ghisalberti & Nepf 2002, Koken & Constantinescu 2023). Due to the difference in hydraulic resistance in the vegetated region and in open water, the shear layer becomes asymmetric about the array interface, forming a two-layer structure (White & Nepf 2008). In contrast to free shear layers, which can grow continuously and symmetrically downstream (Brown & Roshko 1974), the shear layer in partially vegetated channel ceases to grow once the production of shear layer-scale turbulent kinetic energy is balanced by its dissipation by hydraulic resistance (Ghisalberti & Nepf 2004). Consequently, when the shear layer fully developed, the inner penetration scales with the vegetation-induced drag resistance and the outer penetration scales with the pressure gradient (White & Nepf 2007, 2008). The asymmetry effect of mixing layers is weakened as vegetation density decreases as well as bed friction and water shallowness enhances (Wang, Zhang, Jiang, Yao & Yan 2024).

When the growth of shear layer is constrained by the presence of a boundary before it is fully developed, the flow is referred to as a confined flow. Many previous studies have revealed that the flow confinement affects the flow adjustment (Chen et al. 2013, Lei & Nepf 2021) and shear layer evolution (Nepf & Vivoni 2000, Ghisalberti & Nepf 2009). For instance, Chen et al. (2013) observed a faster velocity adjustment and a higher equilibrium interior velocity,

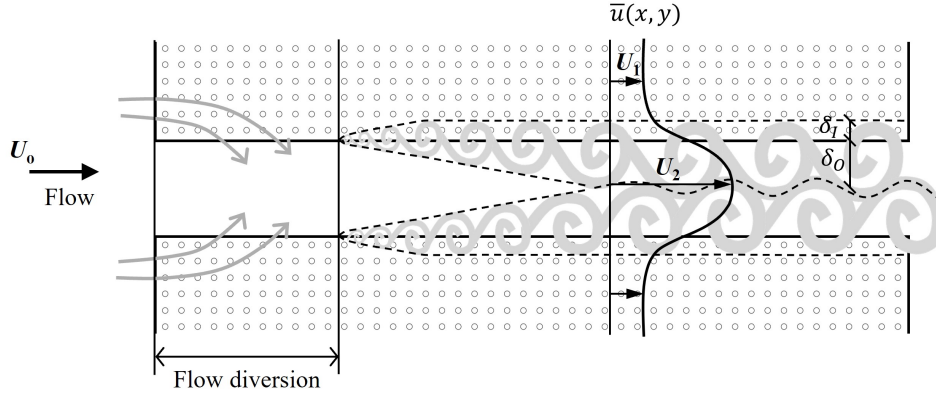


Figure 6.1: Conceptual diagram for flow structure in a symmetrical vegetation-channel-vegetation system. Near the leading edge of the patch, the flow is diverted laterally out of the array over an adjustment length. Shear layers form along each flow-parallel interface, which produce vortices by Kelvin-Helmholtz instability.

$U_1$ , when the submergence ratio of the array ( $H/h$ , where  $H$  is the vegetation height and  $h$  is the water depth) is over a threshold value. Specifically, for vegetation canopies with a frontal area per volume of  $a = 4.4 \text{ m}^{-1}$ , the flow adjustment length remains constant for  $H/h < 0.5$ , but mitigates with decreasing water level for  $H/h > 0.5$ . In addition, Nepf & Vivoni (2000) and Wilson et al. (2003) suggested that the penetration length of coherent structures into the canopy, is constrained by the water surface if  $H/h > 0.5$ . However, the threshold value,  $H/h > 0.67$ , was larger in the study of Nezu & Sanjou (2008), indicating some dependence on canopy density. Similarly, Ghisalberti & Nepf (2009) observed that the water surface constrains the growth of shear layer when  $C_{Da}(h - H) < 0.5$ . When the growth of shear layer was restricted by the water surface, the shear layer stopped growing (Okamoto & Nezu 2013), leading to a reduced shear layer thickness. When the array is sparse or when the vegetation height is low, specifically when  $0.1 \leq C_{Da}H < 0.23$ , the inner shear layer can penetrate the entire array height, so that the penetration would be restricted by the bed (Luhar et al. 2008, Zhang et al. 2020). This penetration highly enhances near-bed turbulence, resulting in increased sediment erosion (Zhao & Nepf 2021). Although submergence ratio can modify the shear structure and the associated vortex's size, the frequency of the KH vortex is observed to always be self-organized (Ghisalberti & Nepf 2002) and consistent with the natural frequency predicted by linear stability theory for mixing layers, Eq. (2.16), (Ho & Huerre 1984). In a partially distributed submerged array, the lateral expansion suppresses the growth of horizontal coherent structures, weakening the horizontal shear stress (Ben Meftah & Mossa 2016). As a result, vertical coherent structures become dominant, leading to enhanced inner penetration (Song, Wang, Duan, Stocchino & Yan 2024). For a partially obstructed emergent array, when the array-to-channel width ratio  $b/B > 0.5$ , where  $b$  is the width of the array and  $B$  is the flume width, the boundary effects

induced by the sidewalls become significant, allowing the along-canopy vortices to trigger the formation of along-wall vortices that rotate in the opposite direction to the original vortices (Jia et al. 2022). This paired-vortices pattern which has been observed on two-dimensional flow past a confined circular cylinder with a blockage ratio  $D/B$  greater than 0.5, where  $D$  is the diameter of the cylinder (Sahin & Owens 2004, Wang et al. 2021). Meanwhile, initiation of the paired vortices enhances the shear-scale turbulence (Jia et al. 2022), and the lateral distribution of the streamwise velocity profile will shift from a hyperbolic tangent to a parabolic velocity profile (Huai et al. 2015). These paired vortices propagate in an alternating pattern, with pronounced reduced wavelength and increased wave number (Jia et al. 2022). The presence of along-wall vortices exerts additional resistance on the main channel flow, highly reducing the bed shear stress, which may facilitate sediment deposition (Jia et al. 2022).

A few previous studies have considered the evolution and interaction between two parallel shear layers. For an in-stream elongated patch, shear layers can develop at two flow-parallel interfaces simultaneously. For a low-flow blockage patch ( $C_{Dab} < 2$ , where  $b$  is the half width of the patch), the inner penetration length is over the patch centerline (Rominger & Nepf 2011), allowing shear layer vortices to interact and merge into a von Karman-like vortex street (Hosseini et al. 2020). This vortex interaction results in a significant velocity recovery and turbulence enhancement within the patch. For a high-flow blockage patch ( $C_{Dab} \geq 2$ ), although shear layers fully develop with penetration less than half the patch width, they can still communicate across the patch width, which highly enhances the strength of the vortices through a wave motion induced by the passage of the vortices along the patch edge (Zong & Nepf 2011, Rominger & Nepf 2011). The wavy motion refers to an oscillating response within the array generated by the passage of vortex, whose center is a low-pressure point (White & Nepf 2007). In contrast to the in-stream vegetation patch with a slow-moving flow within the patch, a symmetrical straight compound channel creates a reverse flow pattern, with a fast-moving flow in the central main channel and a slow-moving flow in the floodplain regions (Proust et al. 2013, Dupuis et al. 2017, Rathod et al. 2025). This flow distribution causes the shear layers formed at the transition regions and associated vortices to rotate oppositely. In a narrow symmetrical compound channel, the shear layers can penetrate to the channel centerline and meet the opposite shear layer, leading to a lateral confinement on shear layer growth (Peltier 2011, Stocchino & Brocchini 2010, Stocchino et al. 2011). However, the interaction of shear-layer vortices in the high-discharge main channel remains insufficiently investigated, especially when two opposite shear layers meet at the channel centerline.

Previous studies have investigated the impacts of flow confinement on velocity adjustment and turbulent structures in scenarios where vegetation is distributed on one side or submerged. However, the scenario where vegetation is distributed on both sides has been rarely addressed, especially when the outer shear layer from one array interacts with the shear layer from the op-

posite array in a high blockage ratio (Figure 6.2). The inadequate research inevitably hinders the full understanding of the mechanics and interactions between vegetation patch and water flow, such as velocity distribution and turbulent structure, making it difficult to predict the sediment transport and morphological evolution for such scenarios that commonly exist in nature aquatic environments. In addition to its eco-hydraulic perspective, this scenario also offers fundamental insights into the mechanics of the interactions between reverse-rotating vortex streets. In this Chapter, we consider a vegetation-channel-vegetation system to investigate the flow structure in a channel with fringing vegetation at both sides (Figure 6.1). This symmetrical configuration creates a high-discharge flow in the central open region and a low-discharge flow in the side vegetated zones, i.e., slow-fast-slow flow pattern reverse to the in-stream vegetated patch (as shown in Chapter 4 and Chapter 5). Correspondingly, the shear layers developed at the lateral interfaces and associated vortices might rotate reversely, similar to a symmetrical compound channel. The flow confinement and turbulent interaction can be explored by varying patch widths. Therefore, the main objectives of this Chapter are (i) to investigate the flow adjustment and shear structure under a symmetrically distributed vegetated channel through scaling analysis; (ii) to examine the initiation and evolution of shear-layer vortices under varying patch widths and densities; (iii) to evaluate turbulent interaction between two parallel shear layers.



Figure 6.2: Aquatic vegetation distributed on both sides of the natural rivers with a high flow blockage. Picture was taken at Dasha River in Shenzhen, China.

## 6.2 Materials and Methods

This Chapter considers 19 tests with varying widths of each array,  $b = 10 \sim 20$  cm, leading to an array-to-channel blocking ratio,  $2b/B = 1/3 \sim 2/3$ . Each array has a length of  $L = 3.7$  m, to ensure the full velocity adjustment and shear layer development. To obtain different array densities, the stem's center-to-center spacing was varied from  $dx = 1$  to 3 cm and  $dy = 2$  to 3

cm in the streamwise and spanwise directions, respectively. The array density, characterized by frontal area per unit volume  $a = Nd$ , where  $N(\text{m}^{-2})$  is the number of rods per unit bed area, ranges from  $3.6\text{m}^{-1}$  to  $16.0\text{m}^{-1}$  and average solid volume fraction  $\Phi = N\pi d^2/4 = 0.9\% \sim 4.0\%$ . The corresponding non-dimensional flow blockage of the array was  $C_{Dab} = 1.85 \sim 13.61$ , where  $C_D$  is the drag coefficient of the array cylinders. Here,  $C_D$  was estimated by,  $C_D = 1 + 10Re_{U_1}^{-2/3}$  (White & Majdalani 2006), where  $U_1$  is the equilibrium velocity after flow adjustment within the vegetated region. The value of  $C_{Dab}$  for all cases is over the threshold value,  $C_{Dab} \geq 0.1$ , for the KH vortex initiation in the partly obstructed channel with emergent array (Ghisalberti & Nepf 2002, Nepf et al. 2007). Experimental configurations are summarized in Table 6.1.

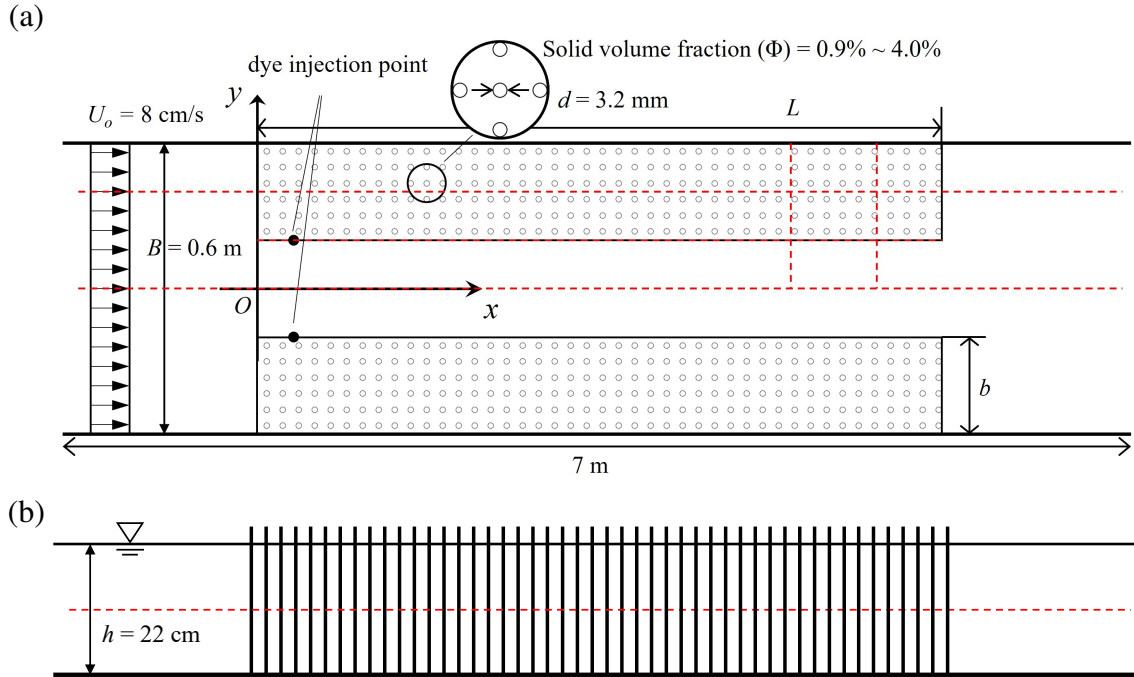


Figure 6.3: The laboratory setup. (a) Top view: illustration of the model array and dye injection points, longitudinal and lateral transects (red dashed lines) of velocity measurements by ADV. (b) Front view: velocity measurements were conducted at the mid-depth. The streamwise and lateral coordinates and velocities are  $(x, u)$  and  $(y, v)$  respectively.

For further analysis, the coordinate system origin was defined as  $x = 0$  at the leading edge of the array, positive downstream,  $y = 0$  at the channel centerline. The velocity components were denoted as  $u, v$  in the  $x, y$  directions, respectively (Figure 6.3a). Measurements were taken along the channel centerline ( $y = 0$ ) and the array centerline ( $y = (B - b)/2$ ) to investigate the flow adjustment. Due to the symmetrical configuration and laterally uniform incoming flow, flow structure was considered symmetrical. Velocities along the channel centerline can also reveal the interaction between the two shear structures formed at the parallel array lateral inter-

| $\Phi$ | $dx$<br>(cm) | $dy$<br>(cm) | $b$<br>(m) | $U_1$<br>(m/s) | $U_2$<br>(m/s) | $u_*$<br>(m/s) |
|--------|--------------|--------------|------------|----------------|----------------|----------------|
| 0.9%   | 3            | 3            | 0.11       | 0.028 (0.001)  | 0.130 (0.001)  | 0.013 (0.005)  |
|        |              |              | 0.14       | 0.033 (0.001)  | 0.141 (0.001)  | 0.015 (0.006)  |
|        |              |              | 0.17       | 0.039 (0.001)  | 0.149 (0.001)  | 0.018 (0.008)  |
|        |              |              | 0.20       | 0.046 (0.001)  | 0.151 (0.001)  | 0.021 (0.008)  |
| 1.3%   | 2            | 3            | 0.10       | 0.024 (0.001)  | 0.131 (0.001)  | 0.013 (0.004)  |
|        |              |              | 0.12       | 0.022 (0.001)  | 0.141 (0.001)  | 0.017 (0.007)  |
|        |              |              | 0.14       | 0.025 (0.001)  | 0.151 (0.001)  | 0.017 (0.007)  |
|        |              |              | 0.16       | 0.029 (0.001)  | 0.160 (0.001)  | 0.019 (0.006)  |
|        |              |              | 0.18       | 0.034 (0.001)  | 0.166 (0.001)  | 0.021 (0.007)  |
|        |              |              | 0.20       | 0.044 (0.001)  | 0.173 (0.001)  | 0.023 (0.007)  |
| 2.0%   | 2            | 2            | 0.10       | 0.019 (0.001)  | 0.135 (0.001)  | 0.015 (0.006)  |
|        |              |              | 0.12       | 0.018 (0.001)  | 0.147 (0.001)  | 0.017 (0.004)  |
|        |              |              | 0.14       | 0.023 (0.001)  | 0.159 (0.001)  | 0.020 (0.007)  |
|        |              |              | 0.16       | 0.027 (0.001)  | 0.171 (0.001)  | 0.021 (0.006)  |
|        |              |              | 0.18       | 0.033 (0.001)  | 0.173 (0.002)  | 0.024 (0.007)  |
|        |              |              | 0.20       | 0.039 (0.001)  | 0.183 (0.001)  | 0.027 (0.009)  |
| 4.0%   | 1            | 2            | 0.10       | 0.013 (0.001)  | 0.141 (0.001)  | 0.015 (0.007)  |
|        |              |              | 0.12       | 0.014 (0.001)  | 0.154 (0.001)  | 0.018 (0.008)  |
|        |              |              | 0.14       | 0.019 (0.001)  | 0.171 (0.001)  | 0.021 (0.006)  |

Table 6.1: Experimental parameters and measured data.  $dx$  and  $dy$  is the stem's center-to-center spacing in the streamwise and spanwise directions respectively.  $U_1$  is the equilibrium velocity after flow adjustment within the vegetated zone.  $U_2$  is the equilibrium velocity after flow adjustment in the main channel.  $u_*$  is the friction velocity across the side edge of the patch, defined in Eq. (6.3). Number in the bracket indicates uncertainty.

faces. To identify the initiation and evolution of the large-scale coherent structures, velocities were collected along one array lateral edge ( $y = B/2 - b$ ). Lateral measurements were only conducted in one half from the side wall to the channel centerline ( $y = 0 \sim 0.8B/2$ ) of the flume to characterize the velocity and turbulence structure. Velocity measurement near the flume wall from  $y = 0.8B/2$  to  $B/2$  was constraint by the ADV holder. At  $y = 0.8B/2$ , no sidewall effect was observed for all scenarios investigated. Lateral measurements were performed at  $x = 2.5$  m and  $x = 3.0$  m, where the flow was verified to be fully developed in all scenarios based on the longitudinal velocity profiles and their comparison between the two transects. To avoid redundancy, only data at  $x = 2.5$  m was included in the subsequent analysis. Velocity measurements were taken every 1 and 10 cm in spanwise and streamwise profiles, respectively. The transects of velocity measurements were denoted by the red dashed lines in Figure 6.3a. The time-averaged lateral velocities ( $\bar{v}$ ) collected at upstream region, fully developed region inside and around the array were all below 1 cm/s (Figure 6.4), indicating that no significant secondary flow occurred in the present experiment.

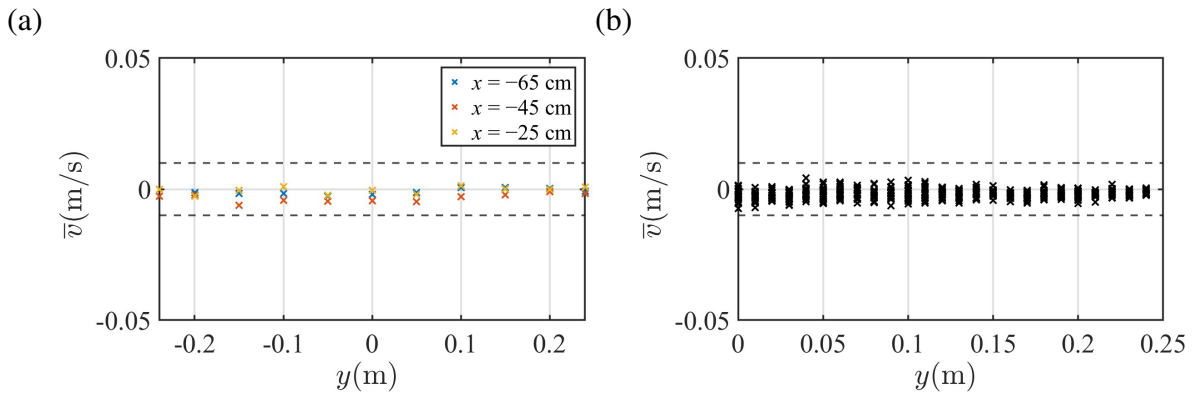


Figure 6.4: The lateral profiles of the time-average lateral velocity ( $\bar{v}$ ) at (a) upstream region, and (b) fully developed region for all scenarios.

Flow visualizations were conducted to describe the flow structure, supporting the velocity measurements. Red dye and green dye were simultaneously injected at 10 cm downstream from two corners of the leading edge ( $x = 10$  cm,  $y = \pm(B/2 - b)$ ) to avoid the strong diverting effect around the leading edge on dye transport. Yellow-colored grid lines with a 10 cm spacing regarding both streamwise and cross-stream directions at the flume bottom were used to provide a distance reference. As the vegetation patches were installed along the side wall of the flume, light-emitting diodes (LED) were positioned around above the flume to illuminate the test section, which can avoid water surface light reflections. More information related to dye test was included in Chapter 3.7.

Other information related to hydraulic conditions, data collection and data treatment method is included in Chapter 3.2, 3.5 and 3.6. For the analysis of velocity measurements, the equi-



librium velocity after flow adjustment within the vegetated zone is defined as  $U_1$ , while the equilibrium velocity after flow adjustment in the main channel is defined as  $U_2$ . The velocity definition can be seen in Figure 6.1.

## 6.3 Results

### 6.3.1 Flow adjustment and shear layer evolution

To investigate the spatial evolution of the shear structures, the distribution of the lateral velocity gradient  $d\bar{u}/dy$  was considered. Here, we define the positions where the lateral velocity gradient equals  $0.1 \text{ s}^{-1}$  as the edge of the shear layer, i.e.,  $d\bar{u}/dy = 0.1$ . Initially, the shear layers with elevated velocity gradient occurred at the leading edge of the array expanded laterally as they developed downstream, gradually approaching the channel centerline. Due to the symmetrical configuration of the system, the velocity gradient ( $d\bar{u}/dy$ ) was always zero at the centerline, presenting a small gap between the two shear layers. However, this gap does not indicate that the shear layers fail to reach the centerline. The highest velocity gradient aligned with the streamwise interfaces, increasing in the streamwise direction. Consistent with previous observations, Figure 6.6 shows a higher velocity gradient near the lateral interfaces of the arrays with a larger vegetation density. However, the growth of shear layer was insensitive to the array density. Moreover, the velocity gradient was insensitive to the array width when the blockage ratio  $2b/B$  was less than 0.5 (Figure 6.7), while the evolution of the shear layers were slightly accelerated. For  $2b/B > 0.5$ , further increased the array width produced a higher velocity gradient and faster shear layer development.

Flow adjustment initiated upstream of the leading edge of the array ( $x < 0$ ) and continued after entering the arrays, varying with array density ( $\Phi$ ) and array-to-channel blockage ratio ( $2b/B$ ). Fluids were deflected from the high-resistance vegetated region to the low-resistance open region, leading to a mitigated velocity interior the vegetated regions ( $U_1$ ) and enhanced velocity in the free stream region ( $U_2$ ). Then, the velocity shear,  $\lambda = (U_2 - U_1)/(U_2 + U_1)$ , across the lateral interface of the array enhanced. As the flow developed downstream, the growth rate of the velocity shear decelerated and eventually reached equilibrium. The developing region is defined as the zone between the leading edge of the patch ( $x = 0$ ) to the position where the velocity shear achieves a constant value ( $\partial\lambda/\partial x \approx 0$ ). Then, the region behind the developing region is defined as a fully developed region. Figure 6.5a observes that increasing the array density ( $\Phi$ ) accelerated the flow adjustment by creating a stronger flow deflection, leading to an improved velocity shear across the interface, as indicated by a larger  $\partial\lambda/\partial x$  and a higher  $\lambda$ . As array width varied (Figure 6.5b), the overlap of  $\lambda$  near the leading edge of the array at different array widths reveals that the lateral flow diversion was independent of the array width. The flow

adjustment was almost identical at  $2b/B < 0.5$ , suggesting that the flow adjustment was not influenced. As  $2b/B$  further increased, the velocity shear reduced, indicating flow confinement presented at  $2b/B > 0.5$ . The influence of the array-to-channel blockage ratio on the flow adjustment is consistent with the findings in a submerged canopy, where a higher submergence ratio ( $H/h$ ) produced a weaker velocity shear at the top interface (Chen et al. 2013).

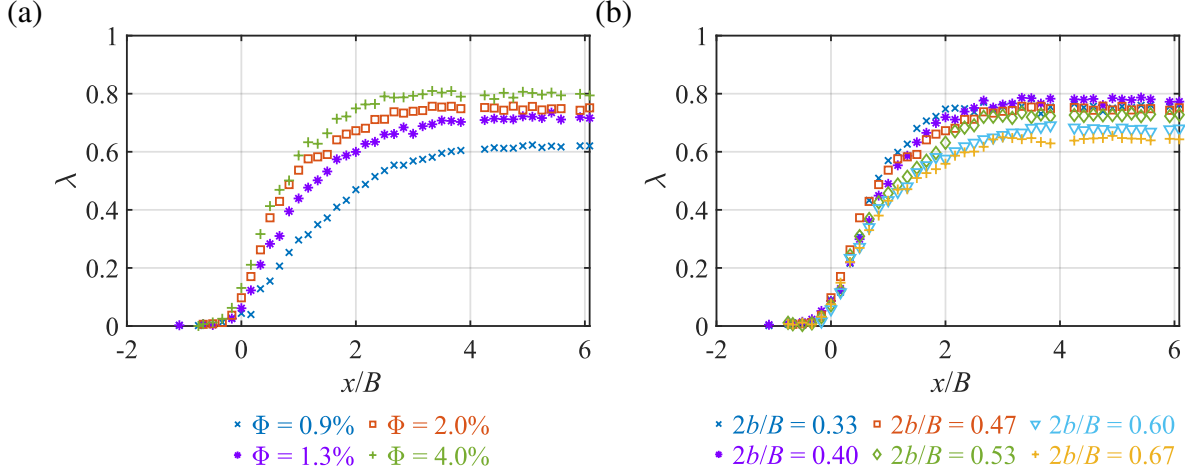


Figure 6.5: The longitudinal profiles of the velocity shear across the lateral interface,  $\lambda = (U_2 - U_1)/(U_2 + U_1)$ , under (a) varying array densities for  $2b/B = 0.47$ , and (b) varying array widths for  $\Phi = 2.0\%$ .

The shear flow near the side edge of each array exhibited a distinct two-layer structure, consisting of a rapidly varying inner penetration,  $\delta_I$  into the vegetated region and a more gradual outer penetration,  $\delta_O$  in the open region (Figure 6.8). Within the shear layer, the shear stress was greatly enhanced, with a peak presenting at the lateral interface. The penetration length is defined as the distance from the side edge of the array to the position where the velocity becomes constant ( $\partial \bar{u} / \partial y \approx 0$ ) and the shear stress approaches zero ( $-\overline{u'v'} \approx 0$ ). A denser array produced a lower interior velocity ( $U_1$ ) and a higher free stream velocity ( $U_2$ ), thereby enhancing the velocity shear (Figure 6.8a, 6.5a). For array with a blockage ratio of  $2b/B = 0.40$ , whose lateral edge located at  $2y/B = 0.60$ , it is observed that the velocity became constant and the shear stress reduced to zero at  $2y/B = 0.10$ , obtaining an outer penetration length of  $0.5(B/2)$  (Figure 6.8). The outer penetration thickness,  $\delta_O = 0.5(B/2)$ , remained constant for a given array width (Figure 6.8), independent on the array density. This observation is consistent with the findings of White & Nepf (2008), who studied a partially obstructed emergent vegetation array with a blockage ratio of  $b/B = 0.33$  and reported that the outer-layer width was governed by the water depth and bed friction coefficient, both of which were held constant in the present experiment.

As the array extended laterally, the outer penetration of the shear layer reduced from the constant thickness,  $\delta_O = 0.5(B/2)$  at  $2b/B < 0.5$ , to the half width of the open region,  $\delta_O = B/2 - b$

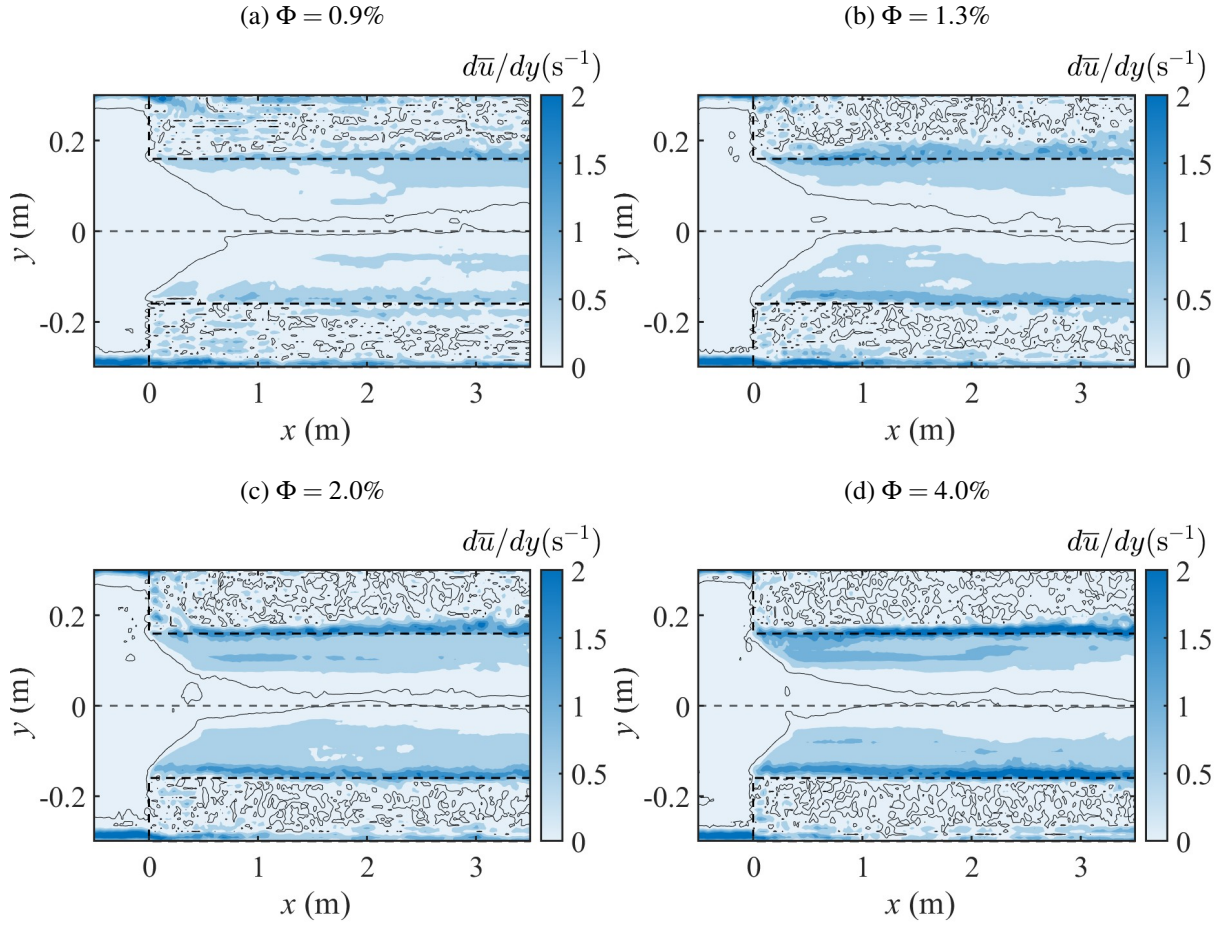


Figure 6.6: The evolution of shear structure indicated by the lateral velocity gradient ( $d\bar{u}/dy$ ), under varying array density for  $2b/B = 0.47$ . The black lines indicate the edge of the shear layer with a threshold value of  $d\bar{u}/dy = 0.1\text{s}^{-1}$ . The dashed line indicate the channel centerline and the edge of the vegetated zones.

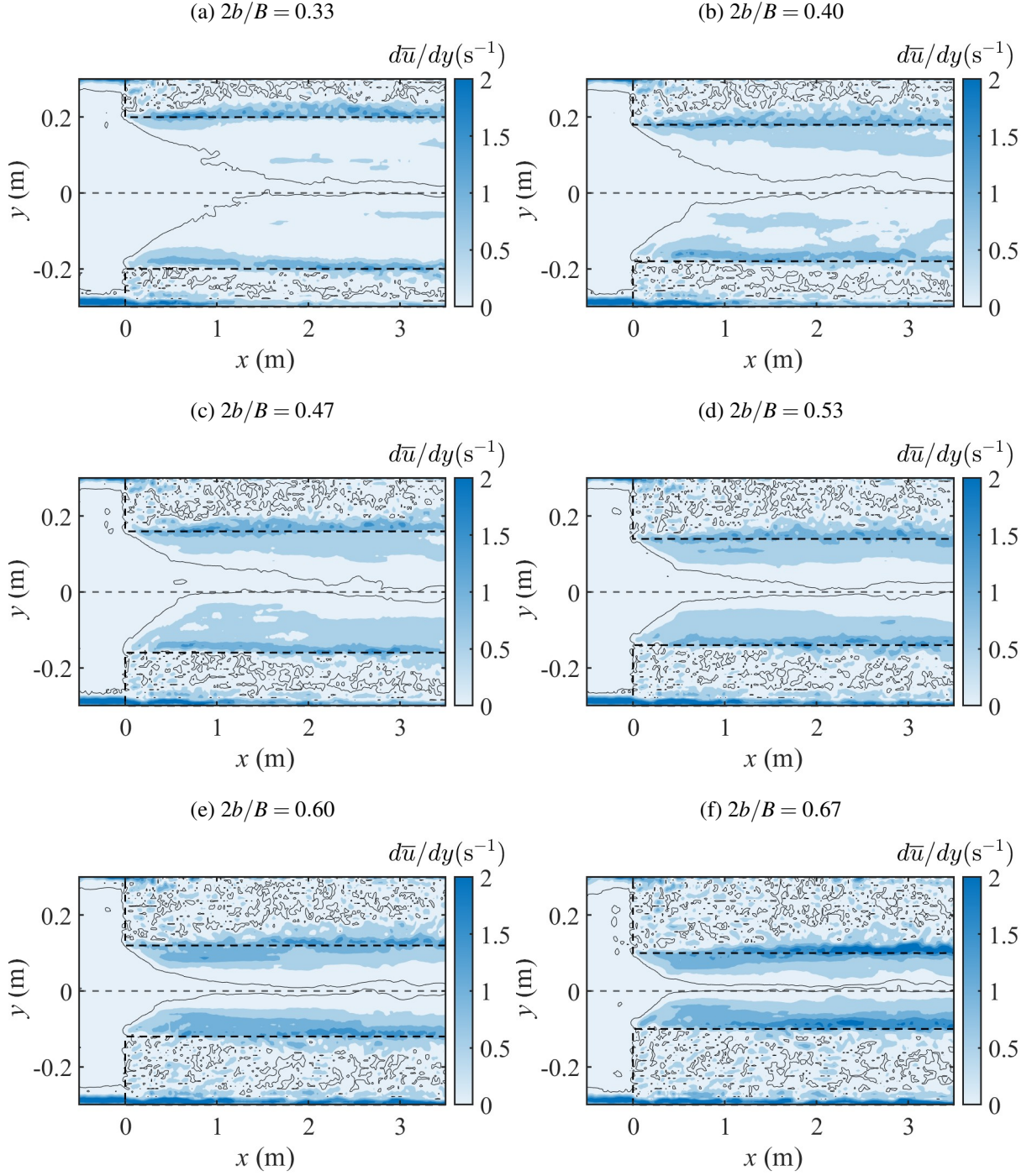


Figure 6.7: The development of shear structure indicated by the lateral velocity gradient ( $d\bar{u}/dy$ ), under varying blockage ratios for  $\Phi = 1.3\%$ . The black lines indicate the edge of the shear layer with a threshold value of  $d\bar{u}/dy = 0.1 \text{ s}^{-1}$ . The dashed line indicate the channel centerline and the edge of the vegetated zones.

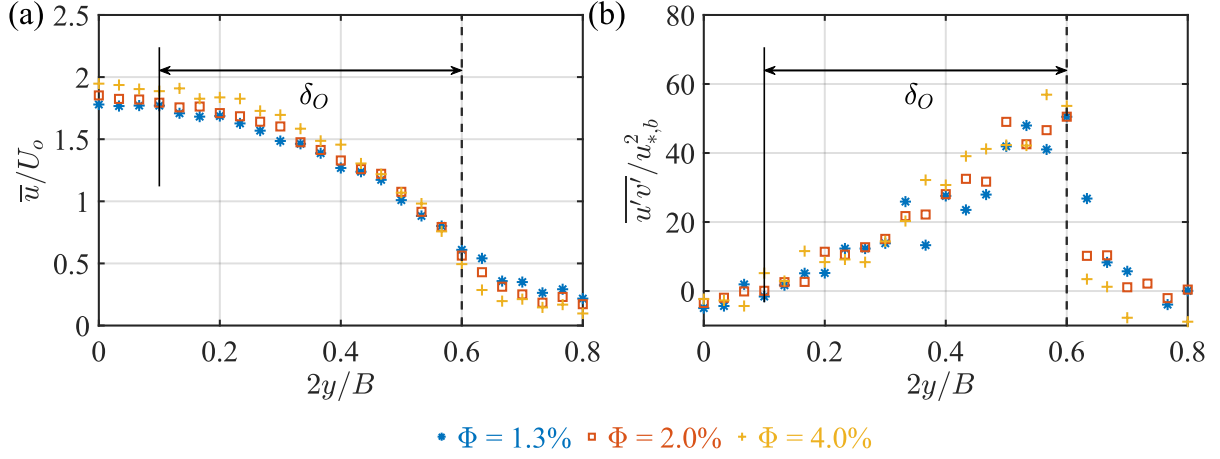


Figure 6.8: The influence of array density ( $\Phi$ ) on the (a) velocity redistribution ( $\bar{u}/U_o$ ) and (b) normalized shear stress ( $-\overline{u'v'}/u_{*,b}^2$ ). Data was collected at fully developed region for cases with  $2b/B = 0.40$ . The dashed line indicates the lateral interface of the array. Here,  $u_{*,b}$  is the bed friction velocity.

at  $2b/B > 0.5$  (Figure 6.9). Specially, at  $2b/B < 0.5$ , the streamwise velocity increased and stabilized before reaching the channel centerline (Figure 6.9a), revealing that the outer layer was fully grown in the open region. The thickness of the outer shear was less than the half width of the open region ( $\delta_O = 0.5(B/2) < B/2 - b$ ). Within the outer shear layer, the shear stress dropped from the peak value at the interface to zero as the velocity became stable (Figure 6.9b). At  $2b/B > 0.5$ , the streamwise velocity continuously increased in the open region, presenting a peak value at the channel centerline (Figure 6.9a). However, the mitigation of the interior velocity diminished, resulting in a higher  $U_1$  and consequently a reduced velocity shear  $\lambda$  (Figure 6.5b). Despite the decrease in velocity shear, the peak shear stress at the interface was highly enhanced (Figure 6.9b). The shear stress decayed continuously in the open region and approached zero at the channel centerline (Figure 6.9b). Consequently, the array with a higher  $2b/B$  experienced a faster shear decay in the open region, as indicated by a larger  $-\partial\overline{u'v'}/\partial y$ . The lateral profile of the streamwise velocity and shear stress shows that the thickness of the outer layer was restricted to the half width of the open region,  $\delta_O = B/2 - b$ , which was less than the full penetration length,  $0.5(B/2)$  in the present work. Given the symmetrical configuration of the system, the shear layers that developed along the two flow-parallel interfaces of the arrays can simultaneously extend toward the centerline, where they may meet and interact (Figure 6.9b). Increasing the width of the open region or removing the opposite array would allow the outer shear layer to continue to expand beyond the channel centerline. Consequently, it is considered that the development of shear layer from one array will be confined by the shear layer developed at the opposite array when they meet at the channel centerline, which will be further analyzed in the following.

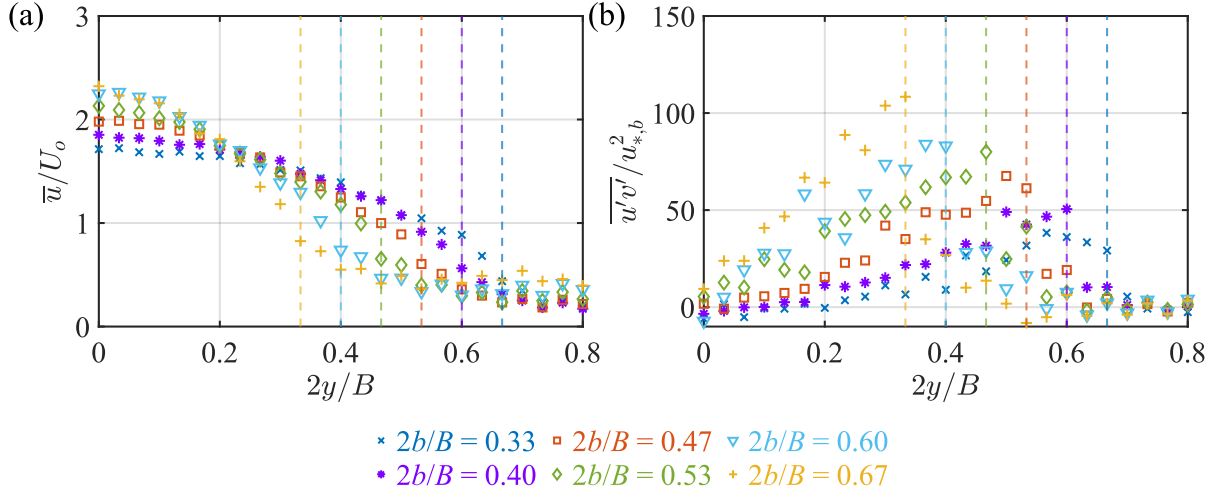


Figure 6.9: The lateral profiles of the (a) normalized time-average streamwise velocity ( $\bar{u}/U_o$ ), and (b) normalized shear stress ( $-\overline{u'v'}/u_{*,b}^2$ ), under varying blockage ratios ( $2b/B$ ). Data was collected at fully developed region for cases with  $\Phi = 2.0\%$ . The dashed lines (with corresponding color of the case) indicate the lateral interface of the array.  $u_{*,b}$  is the bed friction velocity.

In partly vegetated flows, the momentum exchange between the open region and the vegetated region can be analyzed referring to the time-averaged, spatially averaged, and depth averaged two-dimensional shallow water equations (Truong et al. 2019, Caroppi et al. 2021). In the fully developed region, the lateral flow diversion ceased, leading to  $\bar{v} = 0$ ,  $\partial\bar{u}/\partial x = 0$  and  $\partial/\partial t = 0$ . The resulting streamwise momentum equation becomes

$$0 = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x} - \frac{\partial \overline{u'v'}}{\partial y} - F_x, \quad (6.1)$$

where  $\rho$  is the water mass density, and  $F_x$  is the drag force exerted on the fluid in the streamwise direction,

$$F_x = \begin{cases} \frac{1}{2} \frac{C_{Da}}{1-\Phi} \bar{u}^2, & y < B/2 - b \\ \frac{1}{2} \frac{C_f}{h} \bar{u}^2, & y \geq B/2 - b. \end{cases} \quad (6.2)$$

The friction velocity,  $u_*$ , was defined from the peak shear stress at the side edge of the array,  $\tau_i$ ,

$$u_* = \sqrt{\frac{\tau_i}{\rho}} = \sqrt{-\overline{u'v'}_{y=B/2-b}}. \quad (6.3)$$

The shear stress diminishes to zero across the shear layer. For the outer shear layer in the open



region,

$$-\frac{\partial \overline{u'v'}}{\partial y} = \frac{u_*^2}{\delta_O}. \quad (6.4)$$

In the outer shear layer, the shear stress approximately balances the pressure gradient. Eq. (6.1) becomes,

$$\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x} = \frac{u_*^2}{\delta_O}. \quad (6.5)$$

For unconfined shear layer, the shear stress reduced to zero before being restricted by other confinement, leading to a zero gradient of the shear stress,  $-\partial \overline{u'v'}/\partial y \approx 0$ , in the region beyond the outer layer. In this region, the pressure gradient is balanced by bed friction,

$$\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x} = \frac{1}{2} \frac{C_f}{h} U_2^2. \quad (6.6)$$

Substituting (6.5) into (6.6) gets

$$\frac{u_*^2}{U_2^2} \sim \frac{2h}{C_f} \frac{1}{\delta_O}. \quad (6.7)$$

When the shear layers did not penetrate to the channel centerline ( $2b/B < 0.50$ ), a constant value of  $u_*^2/U_2^2$  was observed (Figure 6.10), consistent with the data collected from a single along-bank vegetated channel with a  $b/B = 0.33$  (White & Nepf 2007). This constant ratio confirms that the shear-scale turbulence is balanced by the dissipation by bed friction, leading to a  $\delta_O \sim h/C_f$  (Eq. 6.7) for an unconfined shear layer. The constant ratio of  $u_*^2/U_2^2$  was also valid in submerged rigid canopy with a submergence ratio of  $h/H < 0.5$  in the experiments conducted by Chen et al. (2013) and Ghisalberti & Nepf (2006). However, when shear structure penetrates to the channel centerline ( $2b/B > 0.5$ ), the deviation of  $u_*^2/U_2^2$  in Figure 6.10 reveals that  $\delta_O$  does not scale with  $h/C_f$  any more (Eq. 6.7). As the array expanded laterally (Figure 6.9),  $\delta_O$  was restricted to half width of the open region  $B/2 - b$  and the  $u_*^2$  was highly enhanced (Figure 6.9), which resulted in an enhancement of  $u_*^2/\delta_O$ . According to the balance of pressure gradient and shear stress within the outer shear layer (Eq. 6.5), the pressure gradient in the open region was improved. In unconfined condition, the pressure gradient is balanced by the bed friction. However, in confined condition, the bed friction alone is insufficient to balance the pressure gradient. Due to the symmetrical configuration, the shear layer developed in one array contributed to balancing the shear-scale turbulence from the opposite array, performing like an extra flow resistance. In general,  $\delta_O = \min[c_1 h/C_f, (B/2 - b)]$ , where  $c_1$  is the scaling factor. By fitting the measured data in the present work and data collected from previous studies (Figure 6.10),  $c_1 = 154$ , with a  $R^2 = 0.98$ . This equation suggests that flow confinement occurs at  $c_1 h/C_f + b > B/2$ , where  $c_1 h/C_f$  in the present work is  $0.5(B/2)$ . This yields a threshold

condition of  $0.5(B/2) + b > B/2$ , which simplifies to  $2b/B > 0.5$  for the present experiment. However, when bed friction increases or water depth decreases, the outer shear layer exhibits a reduced full penetration length (i.e., smaller  $c_1 h/C_f$ ). Consequently, the threshold value for flow confinement increases, and a higher blockage ratio is required to generate flow confinement.

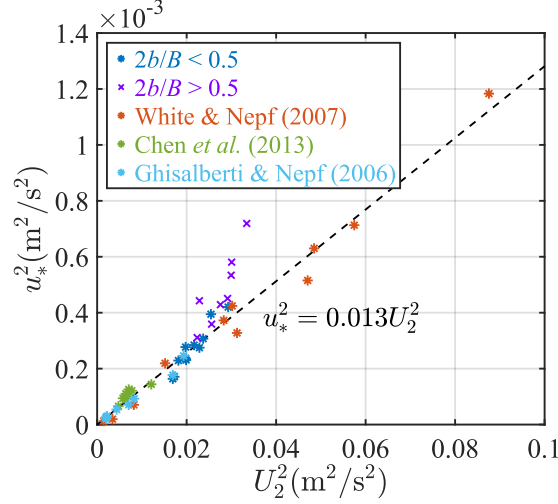


Figure 6.10: Interfacial shear stress,  $u_*^2$  versus  $U_2^2$ . The dashed line is fitted from data in unconfining condition ( $2b/B < 0.5$ ),  $u_*^2 = 0.013U_2^2$ , with a  $R^2 = 0.98$ .

Inside the array, the region outside the inner shear layer has  $-\partial \overline{u'v'}/\partial y \approx 0$ . The pressure gradient was balanced by the drag resistance induced by the plants. Assuming the pressure gradient is constant in the lateral direction and applying Eq. 6.5, the streamwise momentum equation (Eq. 6.1) becomes

$$\frac{1}{2} \frac{C_D a}{1 - \Phi} U_1^2 = \frac{u_*^2}{\delta_O}. \quad (6.8)$$

Thus,

$$\frac{u_*^2}{U_1^2} \sim C_D a \delta_O. \quad (6.9)$$

By fitting the measured data, it is obtained  $u_*^2/U_1^2 = 0.5C_D a \delta_O$  with a  $R^2 = 0.83$  (Figure 6.11a). This agreement suggests the pressure gradient in the open region influences adjustment of the interior velocity (Eq. 6.5 and Eq. 6.8). Specially, an enhanced pressure gradient due to shear layer confinement in the open region leads to a higher interior velocity  $U_1$ , consistent with the observed increase of  $U_1$  with  $2b/B$  in the lateral profiles of streamwise velocity shown in Figure 6.9a. This interior velocity enhancement was also observed in a submerged canopy with a higher submergence ratio (Chen et al. 2013, Lei & Nepf 2021). The submergence ratio, defined as the ratio of vegetation height to water depth, performs similarly to a horizontal blockage ratio in the present work, but applies in the vertical direction.



According to (6.7) and (6.9), we obtain

$$\frac{U_1^2}{U_2^2} \sim \frac{h}{C_f} \frac{1}{C_{Da} \delta_O^2}. \quad (6.10)$$

For unconfined shear layer,  $\delta_O \sim h/C_f$ , (6.10) becomes,

$$\frac{U_1^2}{U_2^2} \sim \frac{C_f}{h} \frac{1}{C_{Da}}, \quad (6.11)$$

which is consistent with the observations in White & Nepf (2007). This shear layer scaling applies to both confined and unconfined shear layers, revealing that flow confinement enhances the interior velocity ( $U_1$ ) and interfacial shear stress ( $-\overline{u'v'}$ ) by improving the pressure gradient.

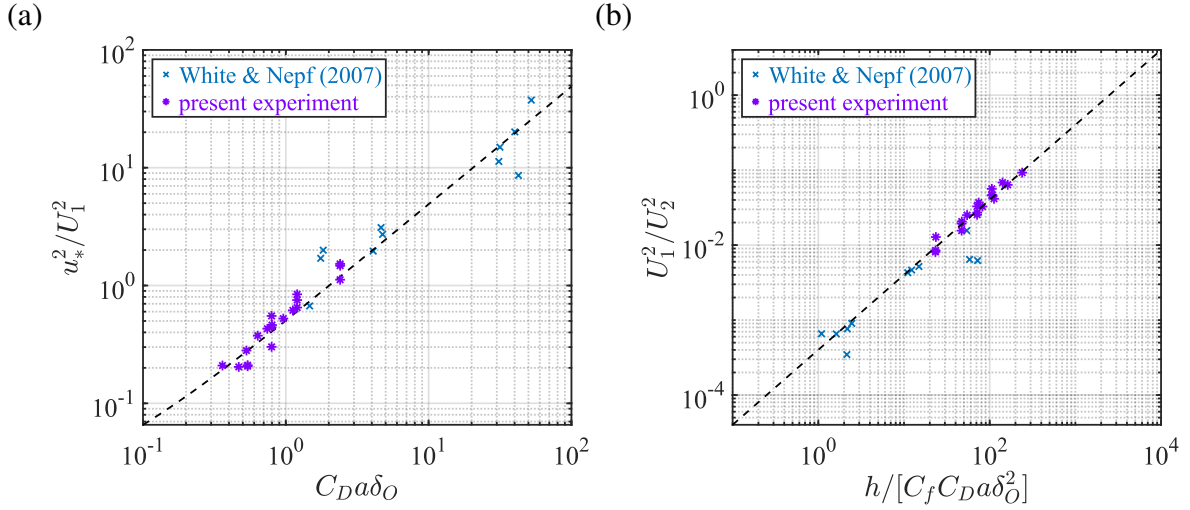


Figure 6.11: (a)  $u_*^2/U_1^2$  scales with  $C_{Da} \delta_O$ . The dashed line is the fitted data,  $u_*^2/U_1^2 = 0.02 + 0.49 C_{Da} \delta_O$ , with a  $R^2 = 0.83$ . (b)  $U_1^2/U_2^2$  scales with  $h/[C_f C_{Da} \delta_O^2]$ . The dashed line is the fitted data,  $U_1^2/U_2^2 = 0.0004 h/[C_f C_{Da} \delta_O^2]$ , with a  $R^2 = 0.92$

### 6.3.2 Vortex formation and interaction

Within the shear layer, the initiation of coherent structures was identified by a distinct peak in the low-frequency region of the cross-power spectral density of the streamwise velocity and spanwise velocity ( $S_{uv}$ , as shown in Figure 6.12 and 6.13). Normalized by the momentum thickness,  $\theta$ , and advection velocity,  $U_c$ , the dominant dimensionless frequency fairly agrees with the value predicted for Kelvin-Helmholtz (KH) instability within a free shear layer,  $f\theta/U_c = 0.032$  (Ho & Huerre 1984). This agreement suggests that the shear instability can self-organize under varying array densities and blockage ratios, even the growth of shear layer was restricted and flow confinement occurs. At  $2b/B < 0.5$ , no peak was observed near the channel centerline,

the absence of turbulent structures as the shear layer had not extended to the centerline (Figure 6.13). However, as the array expanded laterally ( $2b/B > 0.5$ ), a distinct peak emerged at the centerline (Figure 6.13, Figure 6.14), indicating the presence of coherent structure, despite the time-averaged shear stress being nearly zero at this position ( $-\overline{u'v'} \approx 0$  at  $y = 0$ ). The zero time-averaged shear stress and the presence of a peak in the  $S_{uv}$  suggests that turbulent interaction occurred and this interaction resulted in a balancing effect between these two shear layers. Due to the symmetrical configuration, the coherent structures initiated at two interfaces possessed equal strength but rotated in opposite directions. Evaluated by the magnitude of the peaks in  $S_{uv}$ , the vortex intensity was insensitive to the array density, consistent with the observation from the peak of shear stress (Figure 6.8b). However, as the array extended laterally (Figure 6.13), the vortex intensity was highly improved, even though the velocity shear across the interface was mitigated (Figure 6.5b). The consistency of the dominant frequency across the channel width reveals a vortex synchronization between the two vortex streets.

Figure 6.14 shows the turbulent interaction at the channel centerline from the perspective of energy. At  $2b/B > 0.5$ , a  $-3$  slope was observed on the high-frequency side of the peak in  $S_{uv}$ , suggesting that the coherent structures formed were quasi-two-dimensional (Proust et al. 2017, Truong et al. 2019). In the high-frequency region in  $S_{uv}$ , the slope improved from almost horizontal (dark blue in Figure 6.14) to  $-5/3$  as the blockage ratio increased from  $2b/B = 0.33$  to  $0.67$ , indicating the contribution to shear-scale turbulence dissipation was shifted from bed friction to turbulent viscous effect cause by turbulent interaction (Nezu et al. 1994). Furthermore, this improvement reveals that the turbulent interaction highly accelerated the transformation of large coherent structures into smaller scale turbulent structures in the open region (Rathod et al. 2025). This improved transformation is consistent with the faster mitigation of the shear stress in the open region, indicated by larger lateral gradient of the shear stress,  $-\partial\overline{u'v'}/\partial y$  as shown in Figure 6.9b. In addition, the peak and the corresponding frequency improved as the blockage ratio increased, manifesting the enhanced vortex energy and more rapid vortex shedding. For example, when  $2b/B$  increased from  $0.53$  to  $0.67$ , the dominant frequency rose from  $0.15$  Hz to  $0.2$  Hz, indicating that the vortex period decreased from  $6.7$  s to  $5.0$  s at the center of the flume. Within the sampling duration ( $120$  s) in the present work, the number of observed vortices increased from  $18$  to  $20$ , revealing the flow confinement enhanced the vortex shedding at the channel centerline.

The enhancement of dissipation was demonstrated by the PIV analysis at the water surface (Figure 6.15). The dissipation rate was calculated by the Smagorinsky model,

$$\varepsilon = 2(C_s\Delta)^2(\overline{S_{ij}}\overline{S_{ij}})^{3/2}, \quad (6.12)$$

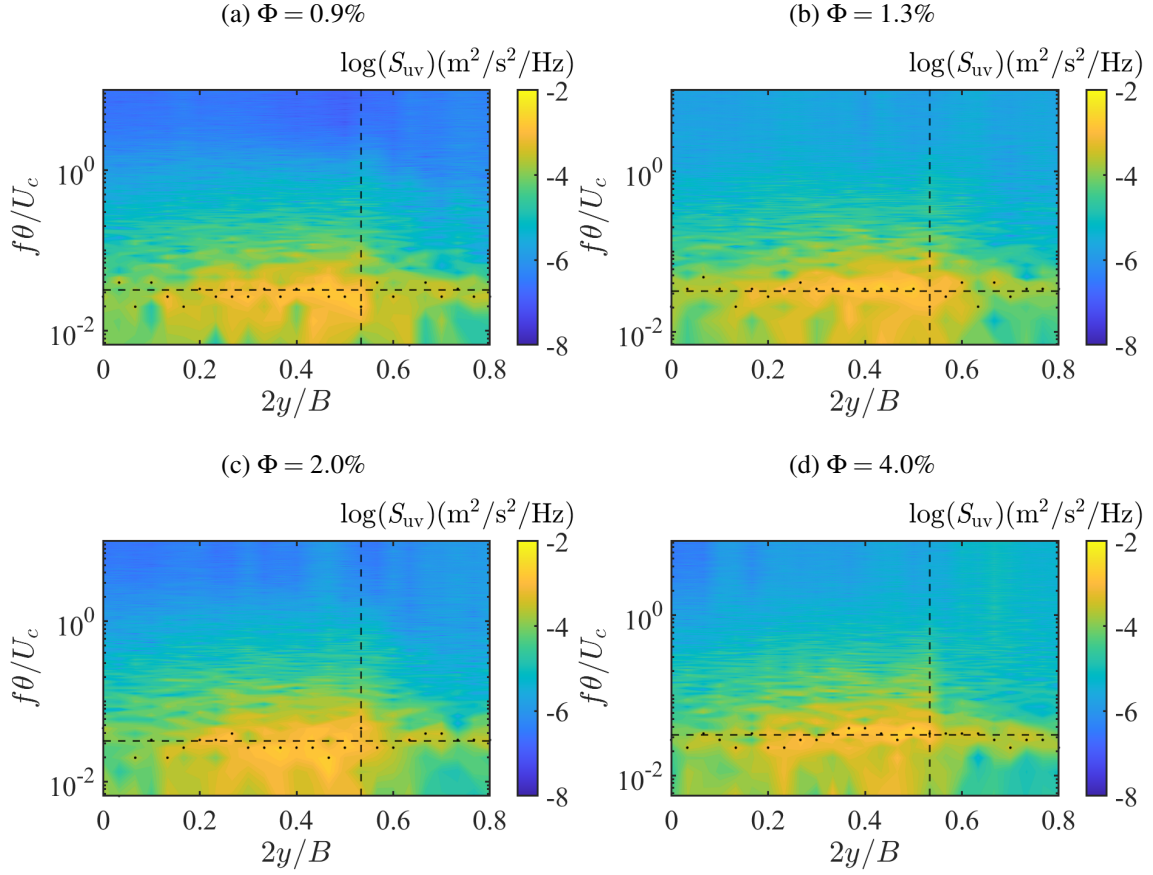


Figure 6.12: Lateral distribution of cross-power spectral density ( $S_{uv}$ ) in fully-developed region at  $2b/B = 0.47$  for varying array density: (a)  $\Phi = 0.9\%$ ; (b)  $\Phi = 1.3\%$ ; (c)  $\Phi = 2.0\%$ ; (d)  $\Phi = 4.0\%$ . The vertical dashed line marks the lateral interface of the array, while the horizontal dashed line indicates the normalized natural frequency of mixing layers,  $f\theta/U_c = 0.032$  (Ho & Huerre 1984). The dots indicate the peak normalized frequencies for each data collected.

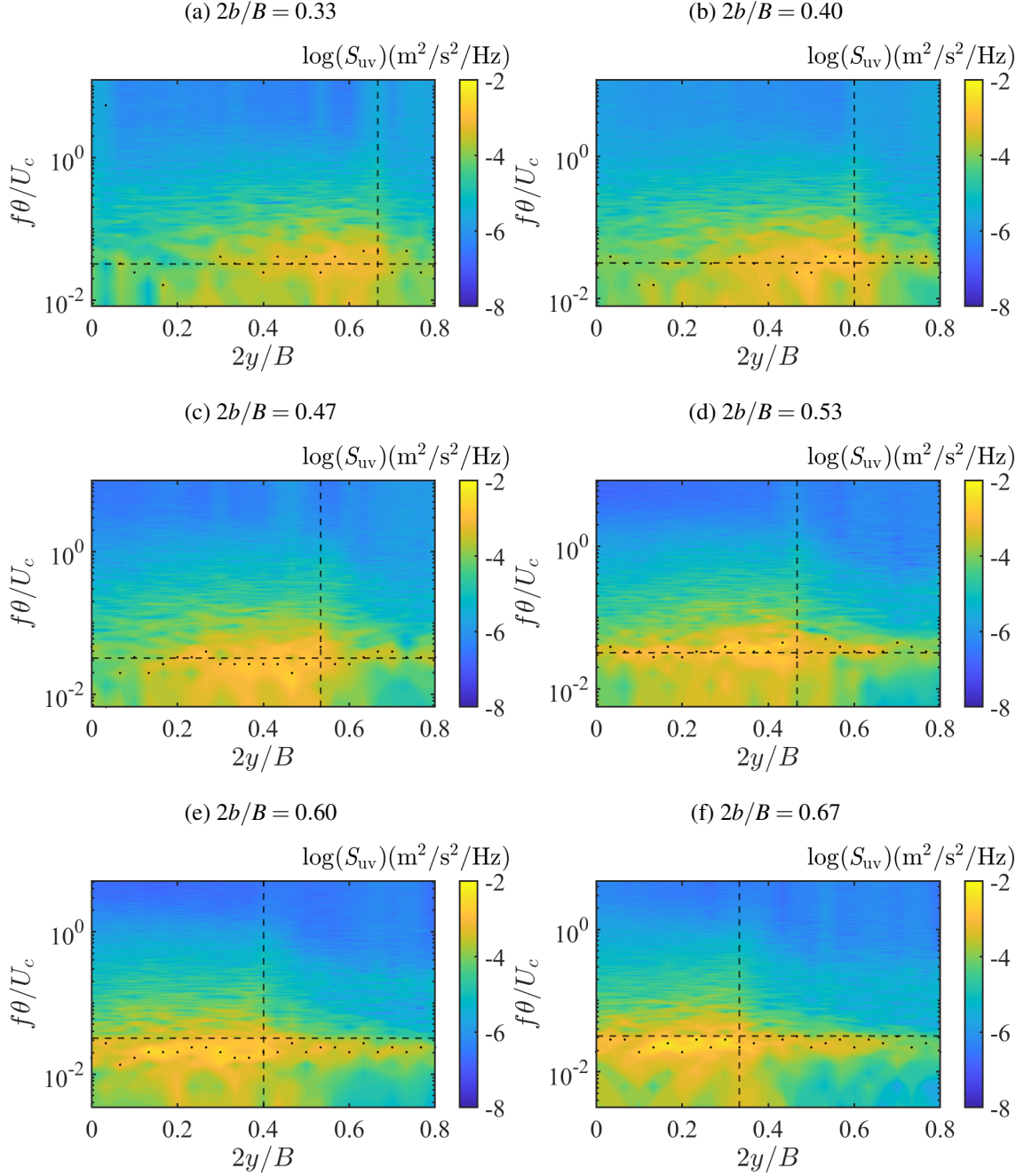


Figure 6.13: Lateral distribution of cross-power spectral density ( $S_{uv}$ ) in fully-developed region at  $\Phi = 2.0\%$  for varying array blockage ratios: (a)  $2b/B = 0.33$ ; (b)  $2b/B = 0.40$ ; (c)  $2b/B = 0.47$ ; (d)  $2b/B = 0.53$ ; (e)  $2b/B = 0.60$ ; (f)  $2b/B = 0.67$ . The vertical dashed line marks the lateral interface of the array, while the horizontal dashed line indicates the normalized natural frequency of mixing layers,  $f\theta/U_c = 0.032$  (Ho & Huerre 1984). The dots indicate the peak normalized frequencies for each data collected.

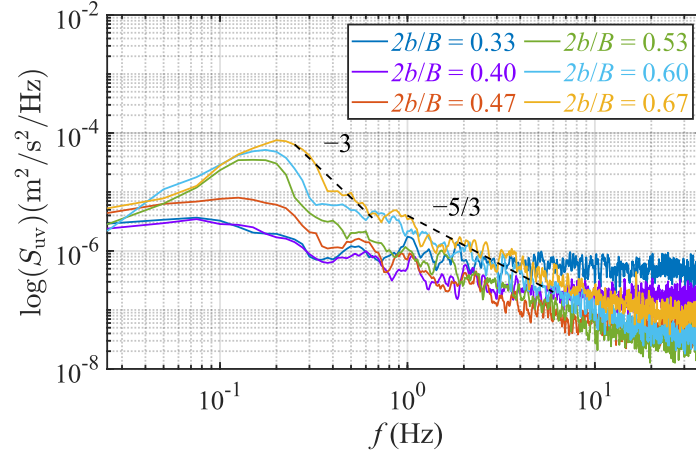


Figure 6.14: The impact of blockage ratio ( $2b/B$ ) on the cross-power spectral density of the streamwise and spanwise velocity ( $S_{uv}$ ) for case with  $\Phi = 2.0\%$  at the channel centerline ( $y = 0$ ).

where  $\bar{S}_{ij}$  is the strain rate tensor,

$$\bar{S}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \quad (6.13)$$

and  $C_s$  is the Smagorinsky constant and  $\Delta$  is the filter width. The highest dissipation rate was concentrated near the interfaces of the arrays, coinciding with the regions where vortices formed. For  $2b/B < 0.5$ , the lateral profiles of patch-averaged dissipation largely overlapped in the open region, indicating that bed friction was the dominant contributor to dissipation. However, as the array further expanded and the blockage ratio exceeded 0.5, the dissipation rates increased significantly both near the array interfaces and within the open region (Figure 6.15a). In this regime, turbulent interaction played a major role in dissipation and bed friction was no longer dominant. Furthermore, higher vegetation density resulted in a greater peak dissipation rate (Figure 6.15b), revealing that intensified coherent structures enhance turbulent interactions and, consequently, the dissipation process.

The normalized frequency of vortex agrees fairly well with normalized natural frequency of mixing layers predicted by linear stability analysis (Ho & Huerre 1984), but the reduction in width of the open region highly improved the frequency of the coherent structures at the side edges, from 0.06 to 0.19 Hz (Figure 6.16a). This is probably due to the reduction in vortex size, which is strongly linked to mixing layer thickness ( $\theta$ , Figure 6.16b), and the increase in advection velocity ( $U_c$ , Figure 6.16c) (Truong et al. 2019). Specially, the reduction in momentum thickness was attributed to the restricted evolution of outer shear layer. These observations complies with previous findings in a single along-bank vegetation canopy (Jia et al. 2022), where decreasing the width of the open region led to a smaller wavelength and wave period of the along-canopy vortices. In their study, the increase in vortex frequency was attributed to the

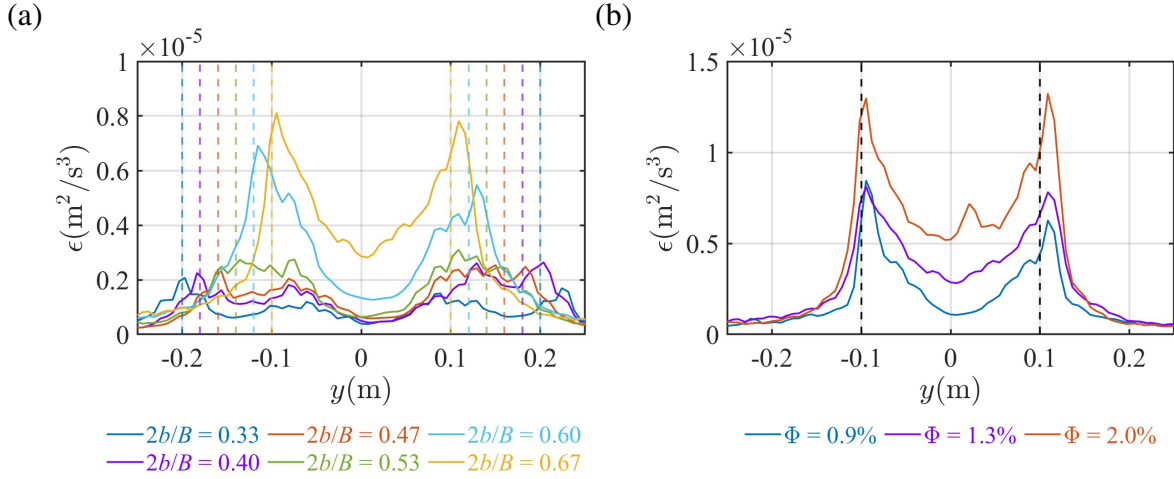


Figure 6.15: Patch-averaged lateral distributions of dissipation rate  $\epsilon$  ( $\text{m}^2/\text{s}^3$ ) calculated using the Smagorinsky model at the water surface: (a) for different array widths at a constant  $\Phi = 1.3\%$  and (b) for different array densities at a constant  $2b/B = 0.67$ . The dashed lines (with corresponding color of the case in (a) and black in (b)) indicate the lateral interfaces of the arrays.

formation of reverse vortices near the side wall of the open region (Jia et al. 2022). Rathod et al. (2025) reported that the enhanced dissipation process due to the presence of steam-scale vortices made contributions to increasing the frequency of the vortices in a compound channel with emergent floodplain vegetation, by breaking the large-scale vortices down into smaller horizontal vortices (Zhang & Hu 2023). In contrast, Wang, He, Dey & Fang (2022a) observed that the reduction in relative submergence of flexible vegetation did not influence the vortex frequency, even though the flow depth overlying the vegetation reduced the spatial scale of the mixing layer. This was because the relative water-blocking area of vegetation intensified the flow turbulence, thereby enhancing the shear layer at the canopy top. In addition, the vegetation density presented no distinct influence on vortex frequency and momentum thickness, since the vortex characteristics were mostly dependent on the outer shear layer in the open region White & Nepf (2007). Overall, the vortex frequency is highly dependent on the vortex size and its correlated dissipation process. Furthermore, the improved frequency means that flow events occur more rapidly. As a result, sedimentation processes may be significantly influenced in such a way that there is less time for the sediment to be deposited, while the momentum fluxes are larger.

To evaluate vortex evolution and to compare the differences in vortex characteristics between the water surface and the middle of water depth, the integral time scales for the streamwise ( $T_u$ ) and spanwise ( $T_v$ ) velocity components were calculated along the side edge of the array. The integral time scale is defined as the integral of the autocorrelation function of a velocity component over time. The autocorrelation function of a velocity component is defined

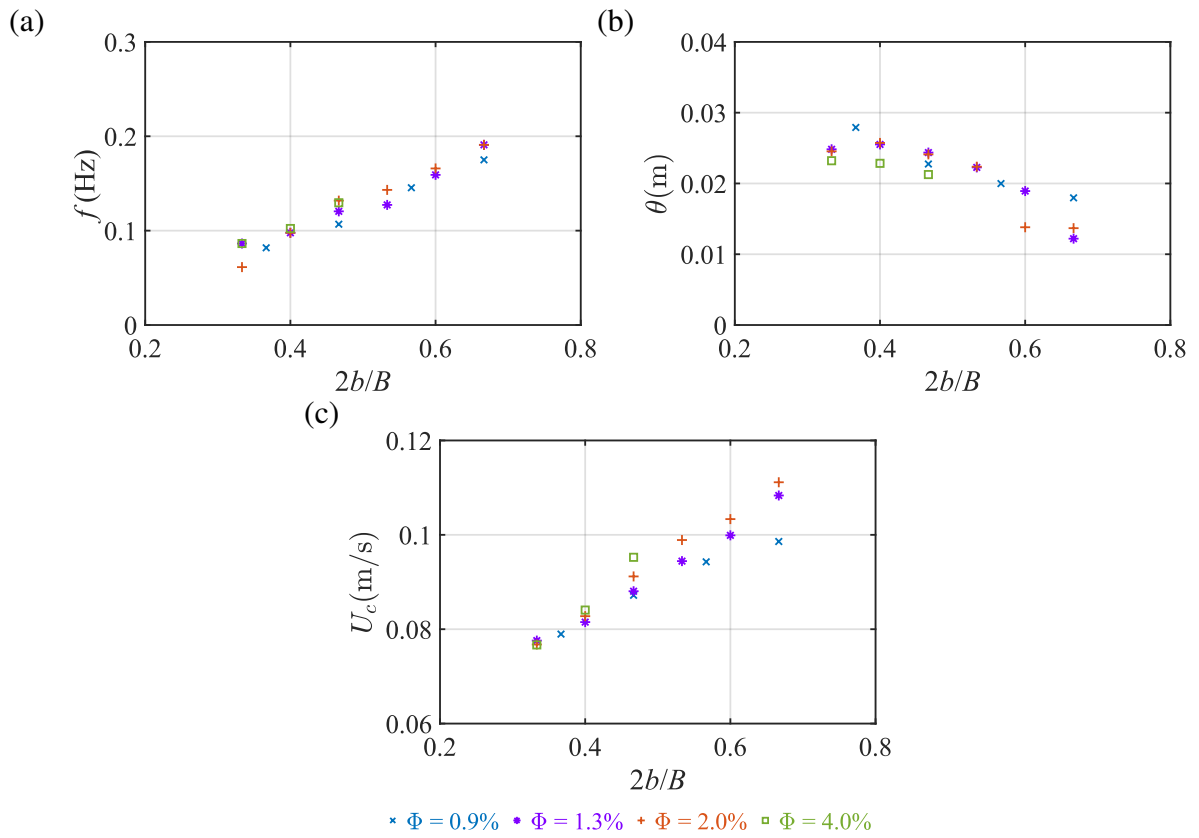


Figure 6.16: The impact of blockage ratio ( $2b/B$ ) on (a) vortex frequency ( $f$ ), collected at the array interface ( $y = B/2 - b$ ), (b) momentum thickness ( $\theta$ ), and (c) advection velocity ( $U_c$ ).

as,

$$R_{u_i u_i} = \frac{\overline{u'_i(t)u'_i(t+\tau)}}{\overline{u'_i(t)^2}}, \quad (6.14)$$

where  $u'_i(t)$  is the fluctuating component of velocity at time  $t$ , including streamwise velocity component,  $u'(t)$ , and transverse velocity component,  $v'(t)$ .  $\tau$  is the time lag. The integral time scale is then calculated by integrating the autocorrelation function from zero to the first zero-crossing,

$$T_{u_i} = \int_0^{\tau_1} R_{u_i u_i}(\tau) d\tau, \quad (6.15)$$

where  $\tau_1$  is the time lag of the first zero-crossing. In Figure 6.17, the streamwise integral time scale ( $T_u$ ) was larger than the transverse integral time scale ( $T_v$ ), indicating that the vortices were elongated in the streamwise direction. In addition, both  $T_u$  and  $T_v$  measured at the water surface were greater than those at the middle of water depth. However, the ratio of the streamwise to lateral integral time scales ( $T_u/T_v$ ) remained consistent between these two positions, indicating that although the vortices increased in size near the water surface, their overall shape did not change. Furthermore, this size difference diminished as the blockage ratio increased. The stable integral time scales in the fully-developed region indicate that the vortices formed were self-sustained, retaining their coherence as evolving downstream.

## 6.4 Discussion

### 6.4.1 Wave response

As the array expanded laterally, the dye released from each array was transported over the channel centerline and the interface between the two dye streaks became wavy, demonstrating that the turbulent interactions created a wave-like response across the open region. The distinct separation of the dye streaks, rather than mixing, suggests that the vortices become self-organized. Although dye was also present at the channel centerline for  $2b/B < 0.5$ , no organized behavior was observed, implying that this phenomenon is attributed to the diffusivity of the dyes rather than vortex evolution (Figure 6.18b). For  $2b/B > 0.5$ , the alternation of the vortex cores from either side of the two arrays in the open region suggests that the vortices organized with a phase shift of  $\pi$  radians (Figure 6.18b). The center of each vortex is a low-pressure point which creates a wave response (Zong & Nepf 2011). In the present work, the alternation vortex cores means that the low-pressure regions in one array corresponded to high-pressure regions in the other array, intensifying the pressure gradient compared to a single interfacial vortex street (Rominger & Nepf 2011). Furthermore, the resulting cross-channel pressure gradient produced a phase shift of  $\pi/2$  radians, analogous with the vortex interaction observed across an in-stream finite porous array (Rominger & Nepf 2011). For a in-stream finite porous patch, cross-patch



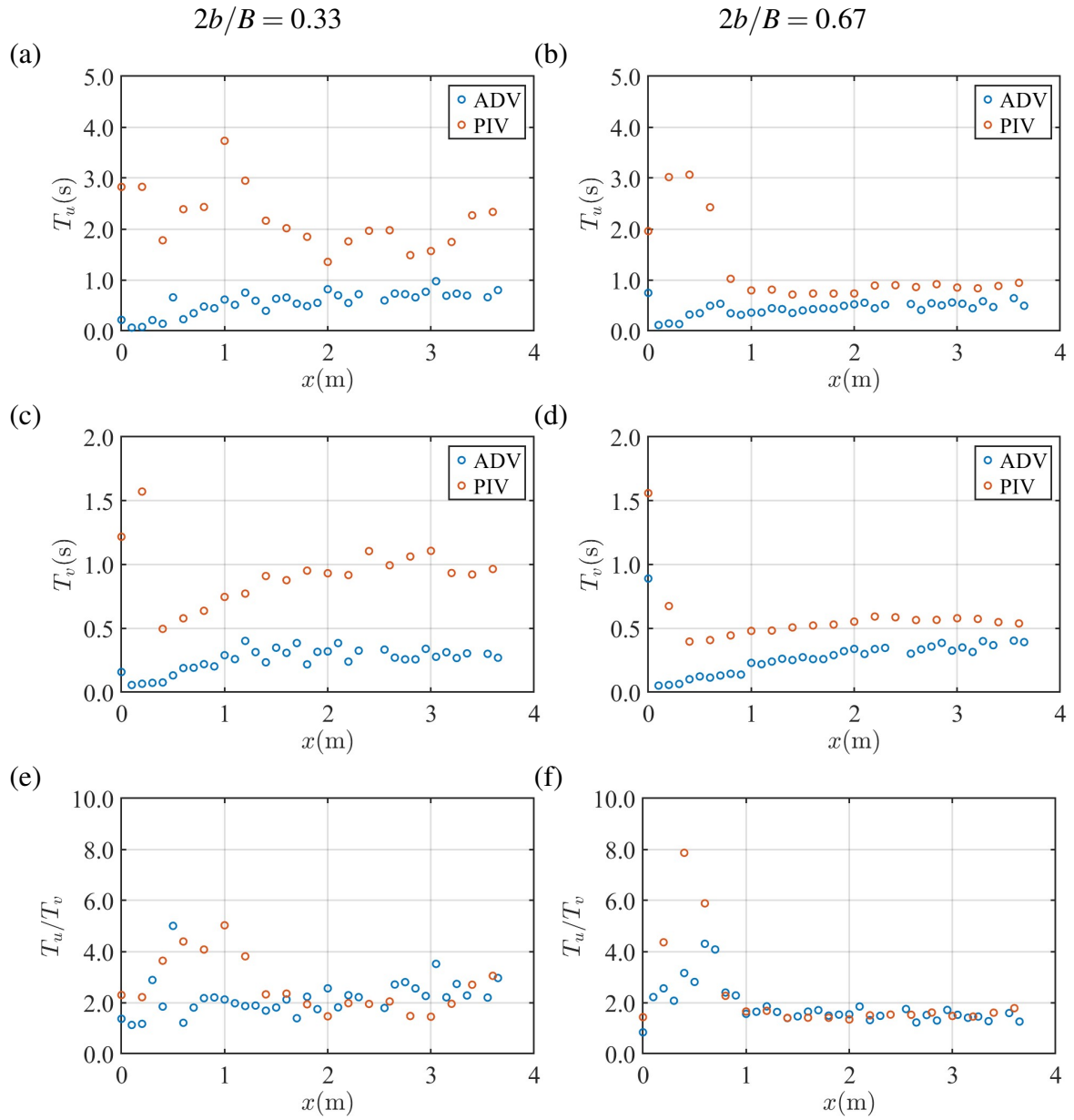


Figure 6.17: The comparisons of the integral time scales in the (a, b) streamwise direction ( $T_u$ ) and (c, d) lateral direction ( $T_v$ ) and (e, f) their ratios ( $T_u/T_v$ ) at the water surface and at middle of water depth.

vortex interaction enhanced the vortex's strength, as indicated by the enhanced magnitude of the peak shear stress compared to the scenario where vortex interaction was prohibited by placing a splitter plate at the patch centerline (Rominger & Nepf 2011). In contrast to the parallel vortices formed along the streamwise interfaces of an in-stream finite patch, where the left side featured an anti-clockwise rotating vortex and the right side featured a clockwise rotating vortex when facing upstream, the parallel vortices in the present experiments exhibited opposite rotation directions. Specifically, when facing upstream, the vortices on the left side rotated in a clockwise direction, while those developed in the right edge rotated in an anti-clockwise direction (Figure 6.1, Figure 6.21). Despite the vortex rotation being reversed, the increase in peak shear stress at higher blockage ratios (Figure 6.9b) demonstrates that turbulent interaction in the open region also contributed to intensifying the vortices by enhancing the cross-stream pressure gradient. Moreover, this interaction improved as the array became more closely spaced. However, the interaction and its corresponding vortex improvement are expected to decay as the array further expands laterally and approaches a channel-spanning patch, which is not considered in the current experiment.

The initiation and interaction of the shear instabilities give the velocity time series a strong periodic signature (Figure 6.19, Rominger & Nepf (2011), Li, Liu & Huai (2022)). The fluctuating streamwise,  $u'(t)$ , and fluctuating lateral velocity,  $v'(t)$  were perfectly out of phase at the array interface ( $y = B/2 - b$ , Figure 6.19a), resulting in a phase shift of  $\pi$  radians. These anti-phase signals made great contributions to the shear stress,  $-\overline{u'v'} > 0$  (Figure 6.8, 6.9). Normalized by the vortex period, the normalized phase shift between the horizontal velocity components converges to a value of 0.5 (Figure 6.19c), indicating that the vortices are well-organized with a phase shift of  $\pi$  radians. Coherence between the streamwise and transverse components at the patch lateral edges exists for all scenarios. In contrast, at the channel centerline ( $y = 0$ , Figure 6.19b),  $u'(t)$  and  $v'(t)$  presented a  $\pi/2$  out of phase, suggesting that the vortices formed at two array re-organized through a wave motion. This is consistent with wavy interface shown in the dye visualization (Figure 6.18) and previous observation (Zong & Nepf 2011, Rominger & Nepf 2011). The phase shift of  $\pi/2$  radians produced no momentum  $-\overline{u'v'} = 0$ , since the peak of one signal was aligned with the zero crossing of the other signal (Figure 6.19b). In this case, due to the symmetrically distributed arrays, the shear stress generated from each interface presented the same magnitude but opposite signs. They balanced each other and produced a zero value at the axis of symmetry, and the lateral gradient of the shear stress was increased. However, the zero shear stress at  $y = 0$  for unconfined channel was due to the limited penetration of the outer shear ( $\delta_o < B/2 - b$ ). The flow beyond the outer shear was relatively steady, presenting a weak and non-coherent velocity fluctuation.

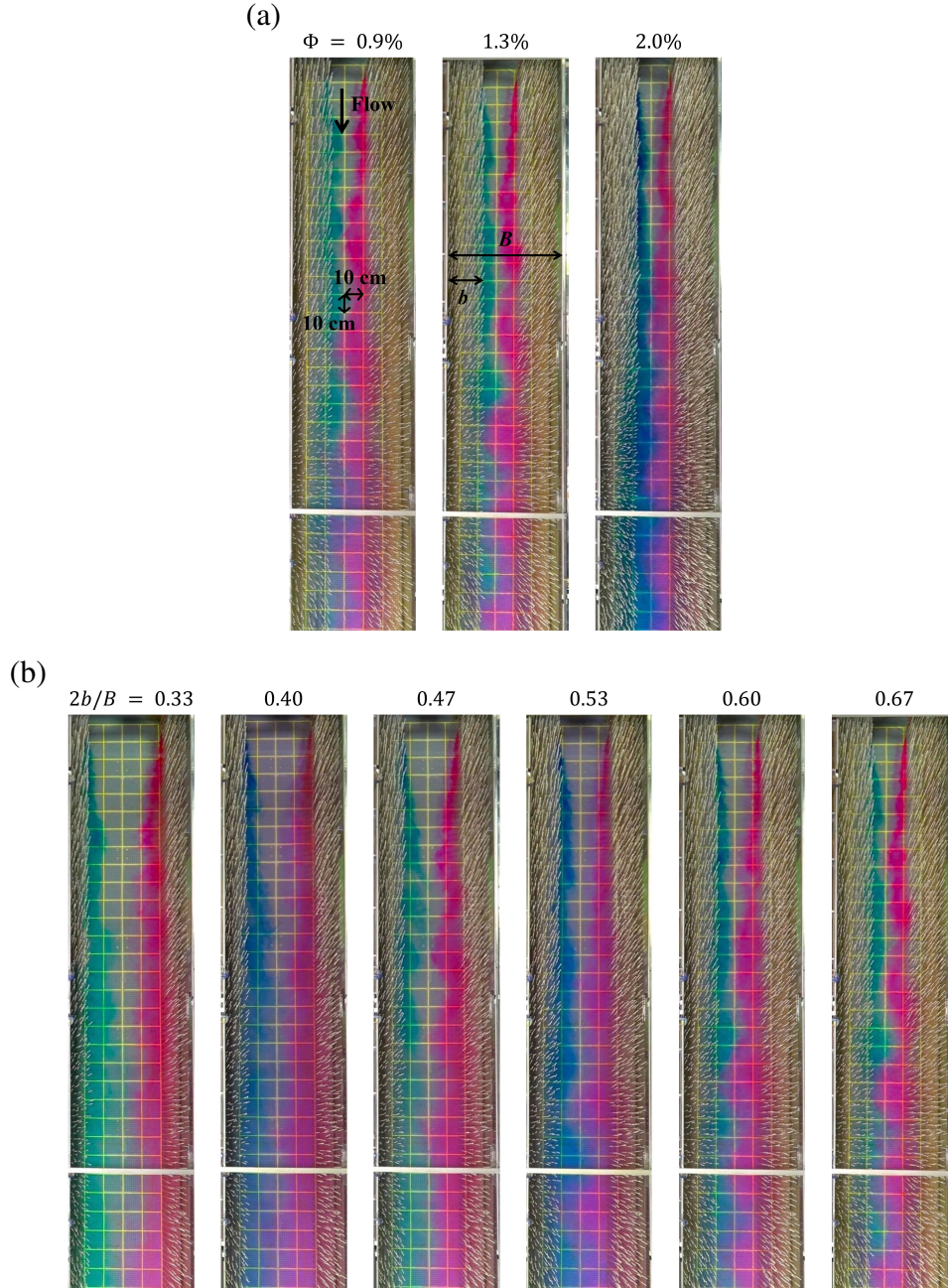


Figure 6.18: Dye visualization test. (a) The alternation of the vortex cores from either side of the two arrays creates a wave response across the main channel, under varying array density ( $\Phi$ ) at  $2b/B = 0.67$ . (b) The impact of the array-to-channel blockage ratio,  $2b/B$ , on vortex structure in the main channel with a  $\Phi = 1.3\%$ . The yellow lines mark 10 cm intervals in both  $x$  and  $y$  directions. The vertical arrow indicates the flow direction. The horizontal arrows indicate the width of the array ( $b$ ) and the flume width ( $B$ ).

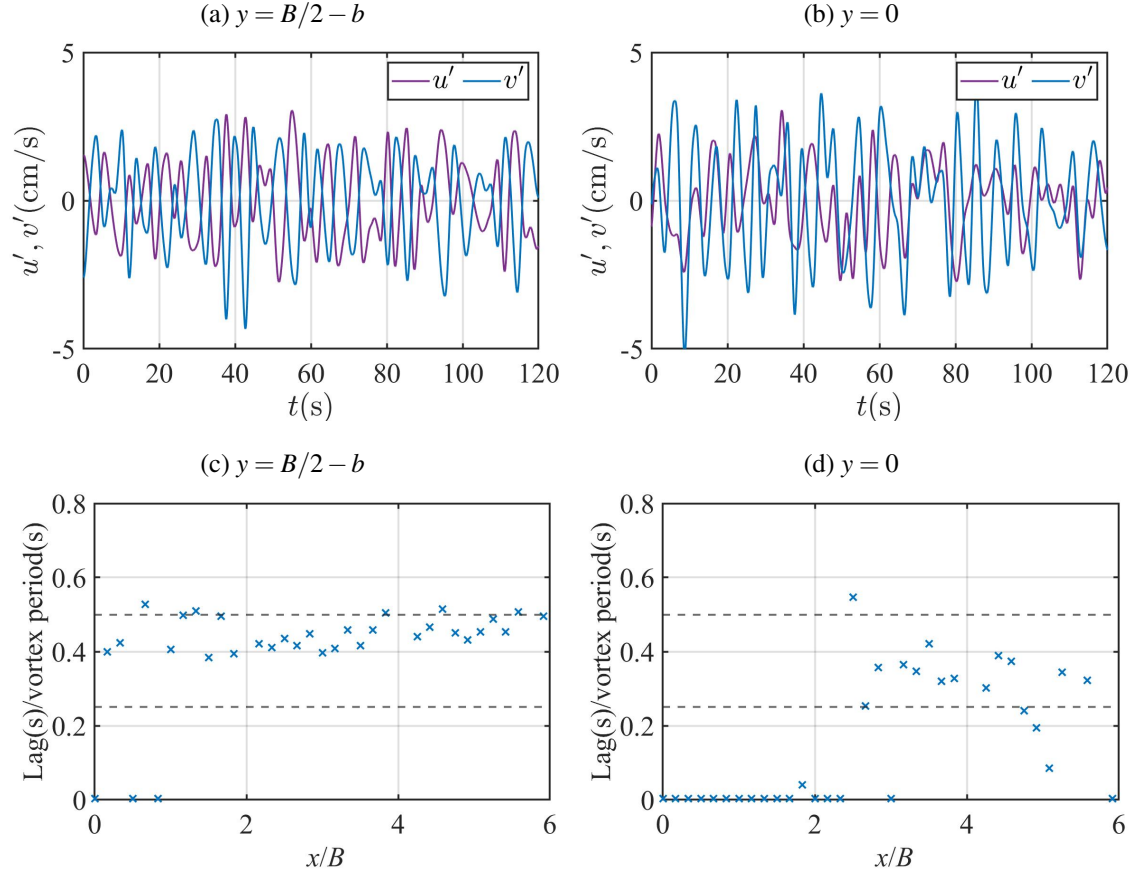


Figure 6.19: (a, b) Time records of fluctuating streamwise velocity,  $u'(t)$ , transverse velocity,  $v'(t)$  and (c, d) their corresponding phase shift at lateral edge of the array,  $y = B/2 - b$ , and channel centerline,  $y=0$ . The time lags between two signals were normalized by the measured vortex period. The data was collected for case with a  $\Phi = 0.9\%$  and  $2b/B = 0.67$ . The dashed line of 0.50 suggests a phase shift of  $\pi$  radians. The dashed line of 0.25 indicates a phase shift of  $\pi/2$  radians.

### 6.4.2 Instantaneous fields at water surface

To provide insights into the instantaneous large-scale coherent structures within the flow-parallel shear layers, a Galilean decomposition was performed on the instantaneous velocity fields (Figure 6.20 and Figure 6.21). This was achieved by subtracting a constant convection velocity of 0.05 m/s from the instantaneous streamwise velocities. Meanwhile, the Okubo–Weiss parameter was evaluated (Okubo 1970, Weiss 1991) to measure the relative contributions of deformation and rotation within the flow. The Okubo–Weiss parameter is defined as the sum of the squares of normal and shear strain minus the relative vorticity,

$$W = \frac{1}{4}(s_n^2 + s_s^2 - \omega^2), \quad (6.16)$$

where  $s_n = \partial u / \partial x - \partial v / \partial y$  is the normal strain component,  $s_s = \partial v / \partial x + \partial u / \partial y$  is the shear strain component, and  $\omega = \partial v / \partial x - \partial u / \partial y$  is the relative vorticity. Positive values of  $W$  represent a strain-dominated flow, while negative values correspond to rotation-dominated flow. In Figure 6.20 and Figure 6.21, a clear alignment between the vortices identified by the Galilean-decomposed velocity vectors and the rotation-dominated regions characterized by negative  $W$  was observed.

Near the leading edge of the arrays, the flow was deflected from the side regions toward the central open region, resulting in increased flow intensity in the open area and reduced flow intensity within the vegetated zones. This flow deflection became more pronounced with increasing vegetation density (Figure 6.20). As the flow deflection diminished further downstream, coherent structures began to form and evolve, eventually reaching an equilibrium size. In addition, a higher array density led to an earlier onset of vortex formation. In contrast to a free shear layer, where the shear-layer vortices tend to bend towards the low-velocity region of the shear layer (van Prooijen & Uijttewaal 2002), the vortices observed in the present work were predominantly located along the interfaces of the vegetation arrays. The presence of vegetation acts as a mechanism for vortex generation. However, no large-scale vortex was detected near the side walls of the channel, suggesting that plant-induced resistance also influences vortex evolution by confining vortices to the low-velocity vegetated regions. A similar phenomenon has been reported in compound channels, where lateral walls serve as a source of vortex generation, yet large-scale vortices were primarily found over the transition region (Stocchino & Brocchini 2010).

As array expanded laterally (Figure 6.21), the vortices initiated at two sides increased in size and became increasingly coherent and organized, especially when  $2b/B > 0.5$ . In this regime, a rotation-dominated region on one side corresponded to a strain-dominated region on the other side, suggesting a phase shift of  $\pi$  radians, which is consistent with the dye observations and ADV analysis in the middle of water depth (Figure 6.19). Furthermore, for all

scenarios considered, we did not observe vortex breaking or vortex merging between vortices originating from different sides, indicating that these vortices remained sufficiently separated despite some turbulent interactions in the open region. The flow intensity was highly enhanced in the strain-dominated regions, oscillating laterally, indicating that the turbulent enhancement was dominated by the flow deformation, rather than the vortex's rotation.

In Figure 6.22 and Figure 6.23, the most significant turbulence enhancement occurred in the open region, contributed by the wave oscillation created by the vortex organization, which is distinct from the single shear layer observed at the lateral edge of partially vegetated channels or at the top interface of submerged canopies, where the peak turbulent kinetic energy aligned with the inflection point of the shear layer. In this symmetrical configuration with vegetation on both sides, even though the shear layers did not extend to the channel centerline ( $2b/B < 0.5$ , Figure 6.22), turbulence intensity in the central region exceeded that near the interfaces. Furthermore, as the vegetation density increases, the turbulence intensity enhanced in the open region. Moreover, as the array expanded laterally, the turbulence intensity in the central region also increased, ultimately becoming concentrated along the wavy trajectory (Figure 6.23).

To further examine the contributions of each velocity component to overall flow fluctuations, the streamwise and transverse fluctuating velocity components were analyzed separately. As shown in Figure 6.24, velocity fluctuations increased with the lateral expansion of the array. Specially, the enhancement of streamwise fluctuations was primarily concentrated at the lateral interfaces of the arrays (Figure 6.24a, 6.24b) while the transverse fluctuations reached peaked near the channel centerline (Figure 6.24c, 6.24d). This pattern suggests that wave motion enhanced turbulence in the open region by amplifying lateral oscillations, with this wave-induced motion largely confined to the open area. The intensified streamwise velocity fluctuations at the interfaces indicate a strengthening of coherent structures near these boundaries, and these structures remained aligned with the array interfaces.

### 6.4.3 Quadrant analysis

Quadrant analysis provides information on the contributions from various events to the turbulent shear stress in the flows (Huai et al. 2019). The four quadrants are associated with four different events, namely outward interactions ( $u' > 0, v' > 0$ ), ejections ( $u' < 0, v' > 0$ ), inward interactions ( $u' < 0, v' < 0$ ), and sweeps ( $u' > 0, v' < 0$ ), respectively. To associate the flow events with the large-scale coherent structure, the time records of the velocity were filtered with a low frequency,  $f = 0.6\text{Hz}$ . The separated low-frequency signals were plotted in the quadrants along with the original measured signals (Figure 6.25) to evaluate the contribution of large-scale coherent structures. The contribution of each event was accounted separately, because the total shear stress was zero at the channel centerline. Figure 6.25a and Figure 6.25b observe that ejection-



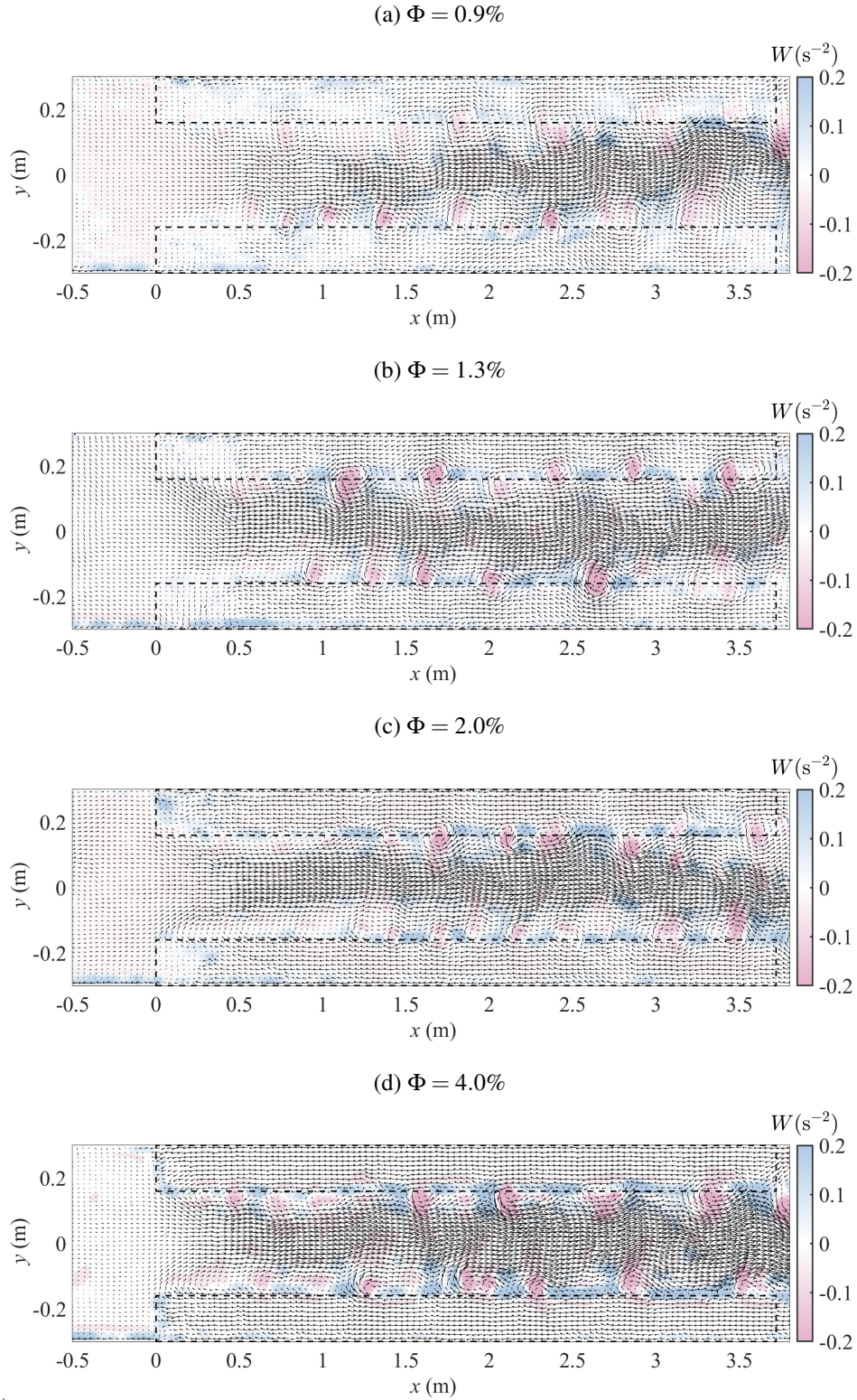


Figure 6.20: Galilean-decomposed velocity vector fields and contour of Okubo-Weiss parameters under varying vegetation densities. The convection velocity used was 0.05 m/s. The dashed lines indicate the interfaces of the vegetated zones.

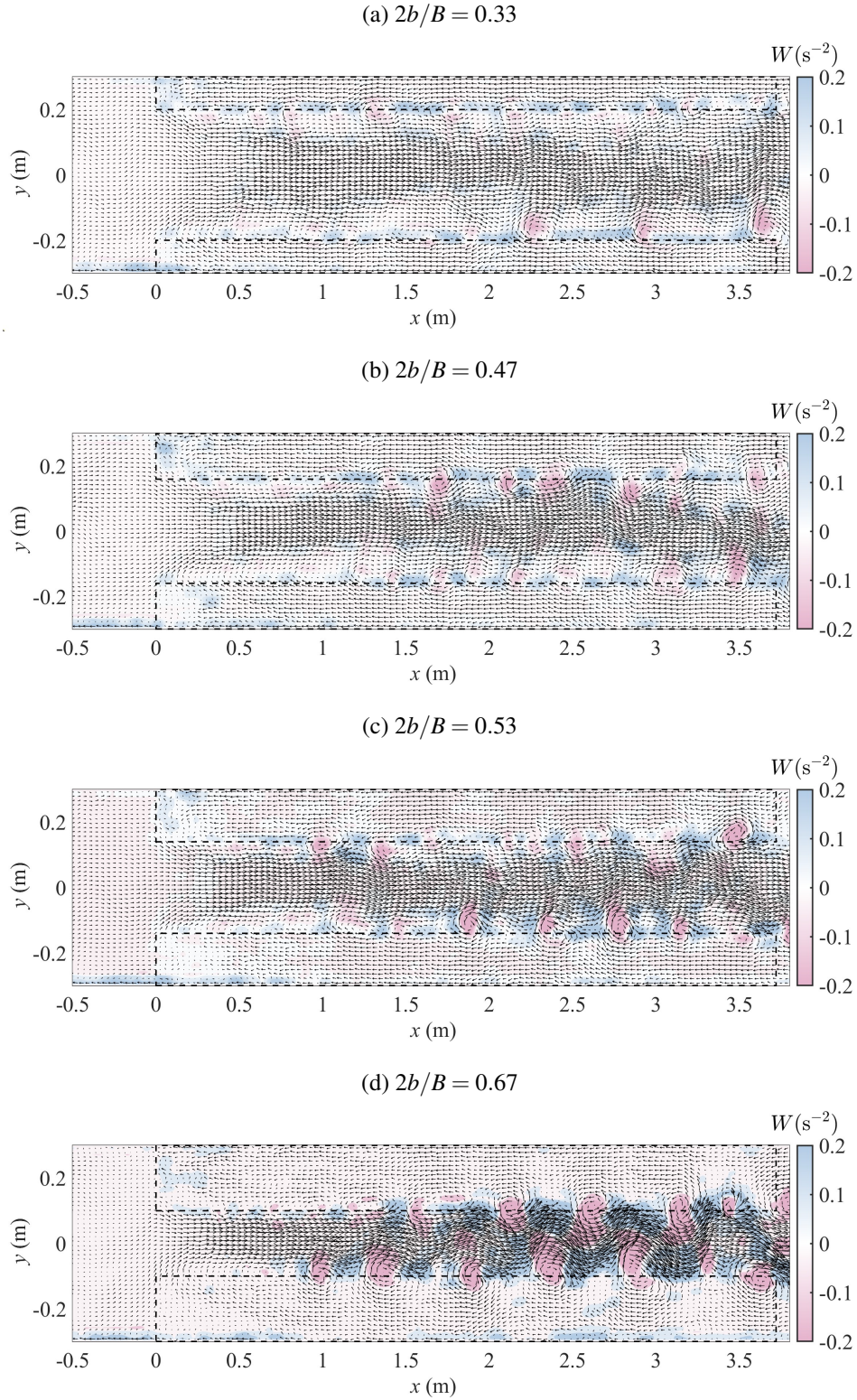


Figure 6.21: Galilean-decomposed velocity vector fields and contour of Okubo-Weiss parameters under varying blockage ratios. The convection velocity used was 0.05 m/s. The dashed lines indicate the interfaces of the vegetated zones.



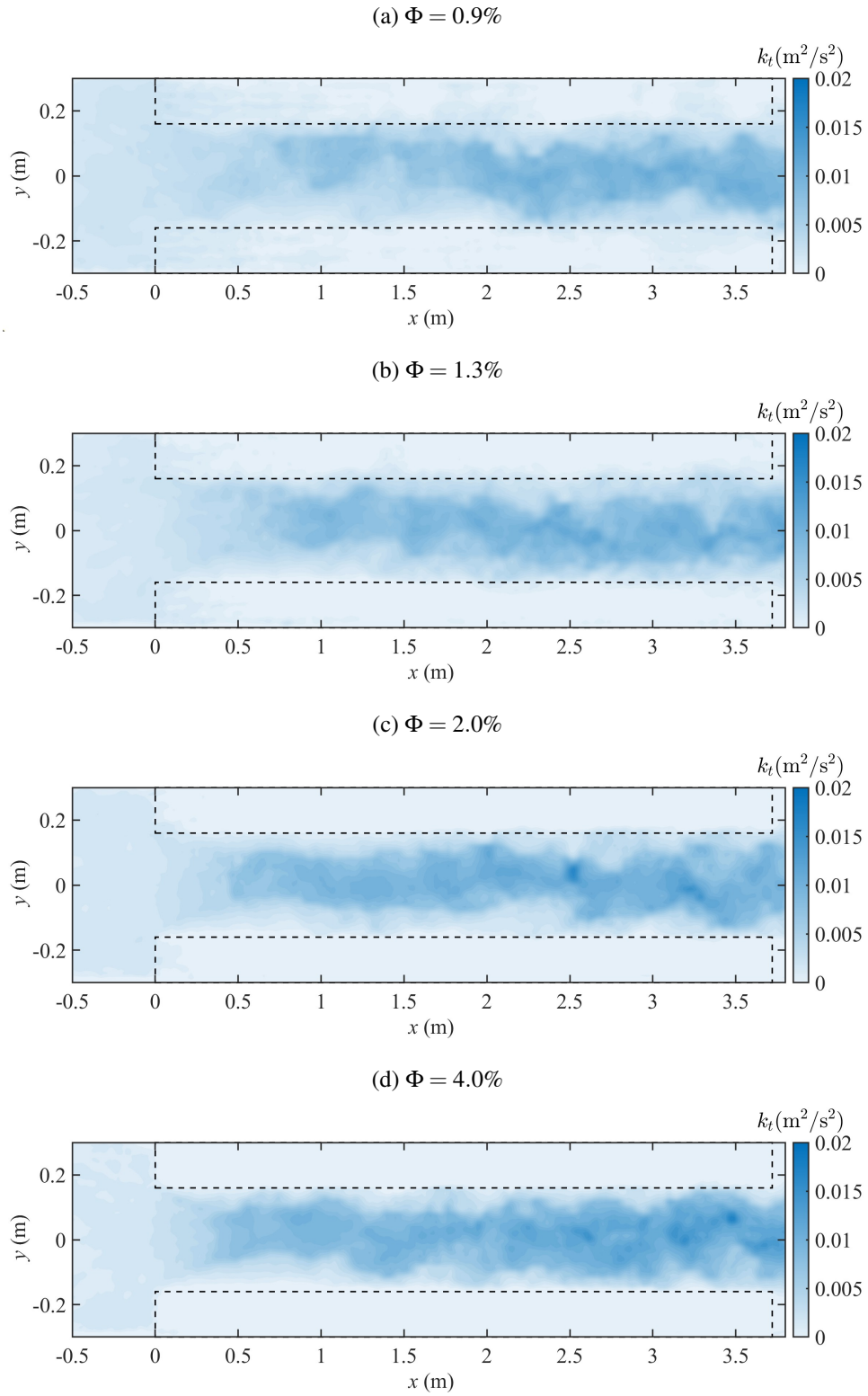


Figure 6.22: The distributions of turbulent kinetic energy ( $k_t$ ) under varying array densities. The dashed lines indicate the interfaces of the vegetated zones.

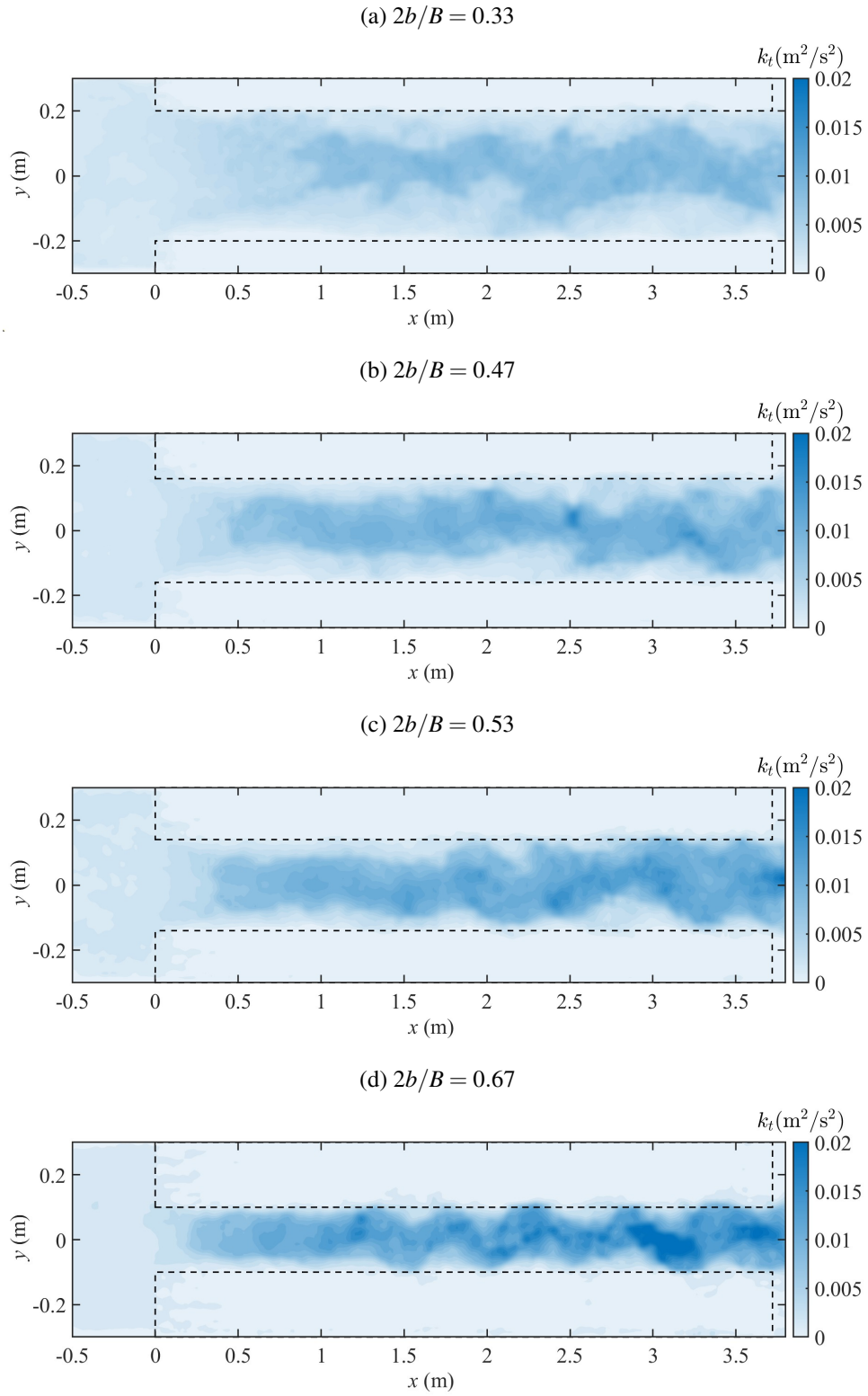


Figure 6.23: The distributions of turbulent kinetic energy ( $k_t$ ) under varying blockage ratios. The dashed lines indicate the interfaces of the vegetated zones.

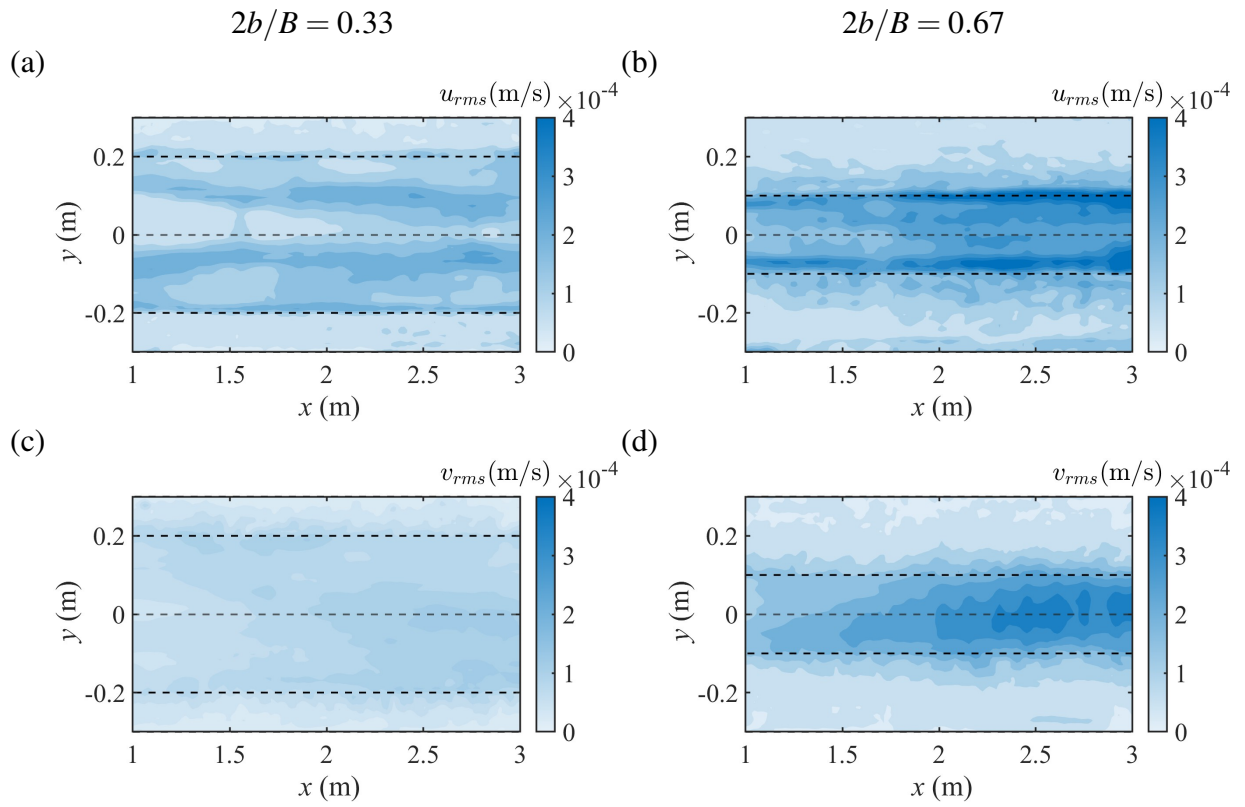


Figure 6.24: The distributions of (a, b) fluctuating streamwise velocity ( $u_{rms}$ ) and (c, d) fluctuating lateral velocity ( $v_{rms}$ ) under varying blockage ratios. The dashed lines indicate the interfaces of the vegetated zones and the centerline of the channel.

tions and sweeps dominated the momentum exchange at the streamwise interfaces of the vegetated zone, in line with the observations in partially vegetated channel (White & Nepf 2008) and compound channel (Truong et al. 2019). For confined shear layers, these events became more pronounced, leading to an improved shear stress near the lateral interface of the array (Figure 6.9b). However, the distribution of flow events associated with large-scale coherent structures (low-frequency signals) varied from the array edge to the channel centerline. In the channel centerline, the contribution of large-scale coherent structures diminished when the shear layers did not extend to the channel centerline (Figure 6.25c), indicating a small influence of large-scale coherent structure at the position. All events intensified as the array widened (Figure 6.25d). The presence of these turbulent events at the channel centerline was clearly visualized by dye (Figure 6.18a). Specially, ejections and sweeps from one array extended across the centerline towards the opposite array, resulting in a wavy interface between the two dyes. Due to the symmetrical distribution of the system, the contribution of ejections and sweeps from one array can be considered as inward interactions and outward interactions from the other array, respectively. The contributions of outward and inward interactions to shear stress are positive ( $u'v' > 0$ ), whereas those of sweeps and ejections are negative ( $u'v' < 0$ ). The distance from the channel centerline to each array was the same, leading to an equal contribution of four turbulent events and a zero net shear stress ( $\overline{u'v'} = 0$ ). Furthermore, even though the shear layer did not extend to the channel centerline ( $2b/B < 0.5$ ), the velocity fluctuation ( $v_{rms}$ ) was improved as the flow developed downstream, around 50% higher than the upstream value (Figure 6.26), attributed to the enhanced flow intensity in the open region. The flow fluctuation was more pronounced when the shear layers were confined ( $2b/B > 0.5$ ), with higher  $v_{rms}$  values observed at larger  $2b/B$ . According to the contribution rate, the improvement in flow fluctuations in the region beyond the shear layer was not dominated by low-frequency structures. As the shear layers reached the centerline, all four events made significant contributions (Figure 6.25d), indicating that the momentum exchange shifted from ‘jet-dominated’ to ‘shear-dominated’. The intensified flow fluctuations and turbulent events suggest that momentum exchange occurred across the channel centerline.

Turbulent events at the two lateral edges of the arrays along the same lateral transect can be evaluated using the time series of fluctuating velocity components collected at the water surface by PIV analysis (Figure 6.27). The time records of fluctuating streamwise velocity ( $u'$ ) at two lateral edges of the arrays were completely out of phase: when one edge exhibited a peak value of  $u'$ , the other reached its lowest value (Figure 6.27a). In contrast, the time records of fluctuating transverse velocity ( $v'$ ) was consistent across the channel (Figure 6.27b), indicating the vortex synchronization and the presence of wave motions. This pattern suggests that when ejections ( $u' < 0$ ,  $v' > 0$ ) occurred at one edge, the corresponding  $x$  position at the opposite edge experienced outward interactions ( $u' > 0$ ,  $v' > 0$ ). Similarly, when sweeps ( $u' > 0$ ,

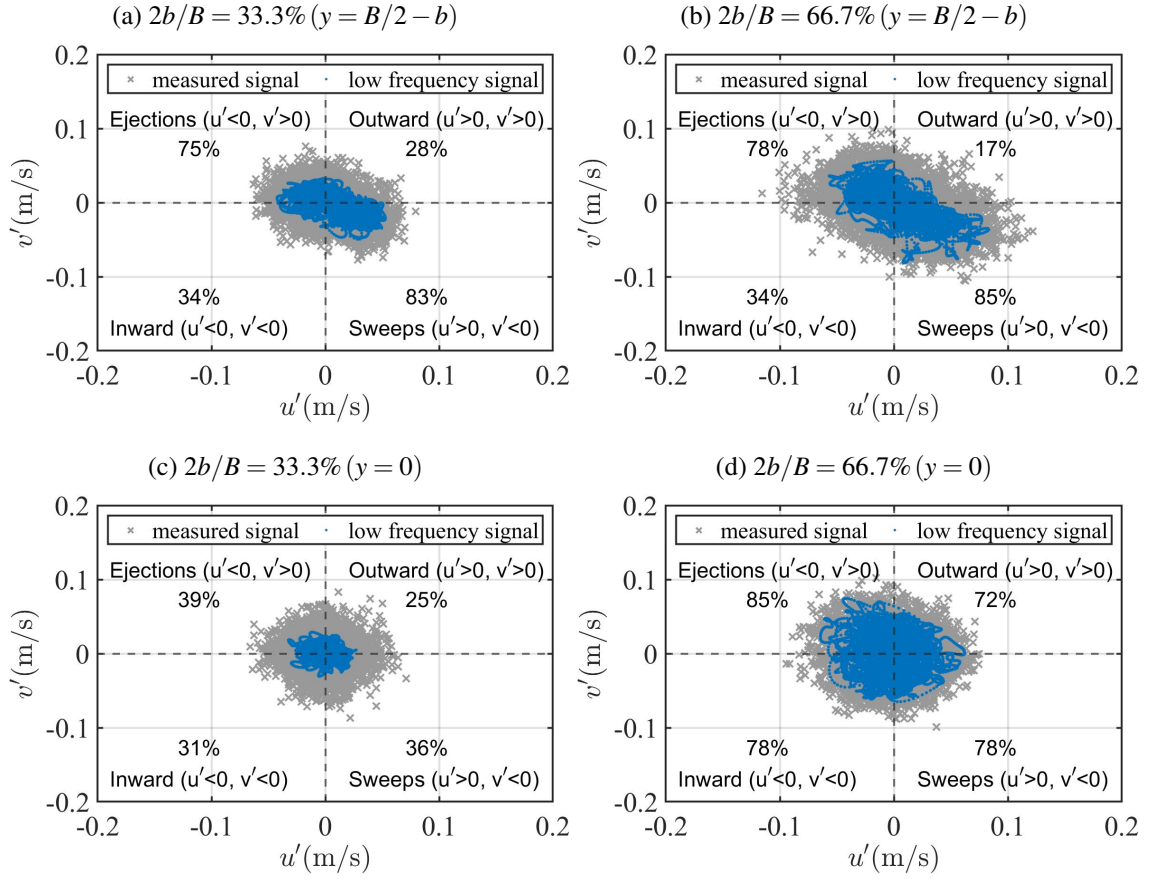


Figure 6.25: The contribution of large-scale coherent structures to each flow event. The data was collected (a, b) at the lateral interface of the array and (c, d) channel centerline in the fully developed region, before ( $2b/B = 33.3\%$ ) and after ( $2b/B = 66.7\%$ ) shear layer penetrating to the centerline. The percentage at each quadrant indicates the contribution from the corresponding event.

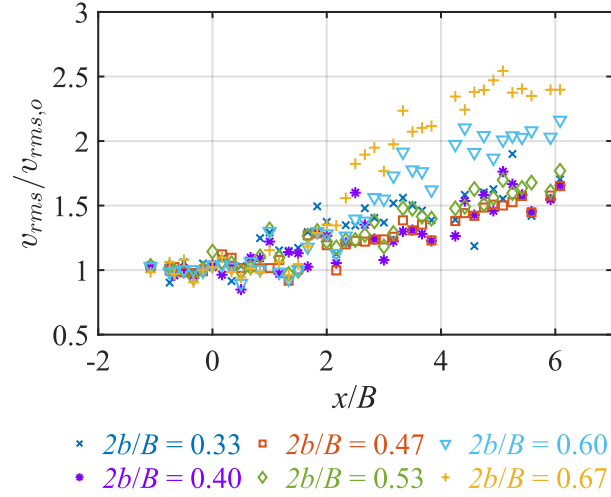


Figure 6.26: The enhancement of fluctuating lateral velocity ( $v_{rms}$ ) at the channel centerline under varying blockage ratios ( $2b/B$ ), normalized by upstream fluctuating lateral velocity,  $v_{rms,o}$ .

$v' < 0$ ) occurred at one array, the opposite edge experienced inward interactions ( $u' > 0$ ,  $v' > 0$ ). Consequently, on one side, the fluctuating streamwise and lateral velocities ( $u'$  and  $v'$ ) were completely out of phase (Figure 6.27c), while on the other side, they were fully in phase (Figure 6.27d). This resulted in positive shear stress on one side ( $-\overline{u'v'} > 0$ ) and negative shear stress ( $-\overline{u'v'} < 0$ ) on the other (Figure 6.28).

#### 6.4.4 Momentum transport

Compared with a single vortex street, the momentum transport in the open region with turbulent interaction is more complicated. On one hand, the phase shift induced by vortex organization between the two parallel vortex streets in the open region enhanced the pressure gradient between low-pressure vortex cores, thereby improving flow fluctuations. On the other hand, the vortex frequency was increased, which means that the resident time for the momentum transport was reduced. Considering the improved momentum fluxes and diminished resident time, we applied the wave excursion length (Nepf 2012a, Luhar & Nepf 2016),  $\Lambda = \sqrt{2}v_{rms}/2\pi f$ , to estimate the lateral transport distance from the array interface. The frequency of the wave motion was consistent with the passing vortices (Zong & Nepf 2011), as indicated by the consistent frequency in  $S_{uv}$  across the channel in Figure 6.12, and the fluctuating lateral velocity at the lateral interface was used. Figure 6.29a observes that the excursion decayed from  $\Lambda = 0.8b$  to  $0.2b$ , as the blockage ratio increased. Although the turbulent interaction in the open region improved the flow fluctuations, the enhanced frequency and resulting reduced excursion length suggest that the lateral transport was restricted. Thus, for one shear structure, the presence of an opposite shear structure restricted the lateral momentum transport. In contrast, for a finite

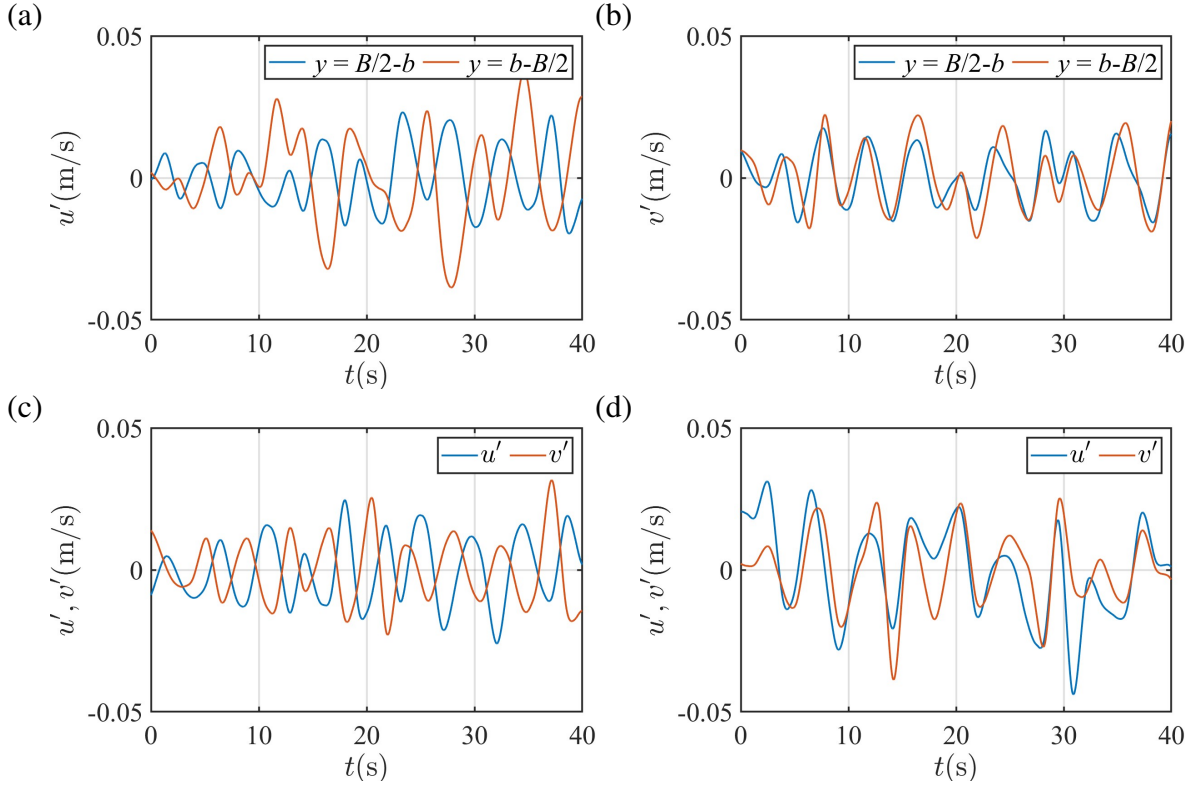


Figure 6.27: Time series of (a) fluctuating streamwise velocity,  $u'(t)$ , and (b) fluctuating transverse velocity,  $v'(t)$ , measured at both lateral edges of the arrays,  $y = \pm(B/2 - b)$ . Panels (c) and (d) show the time series of  $u'(t)$  and  $v'(t)$  at each lateral edge, specifically at (c)  $y = B/2 - b$  and (d)  $y = b - B/2$ .

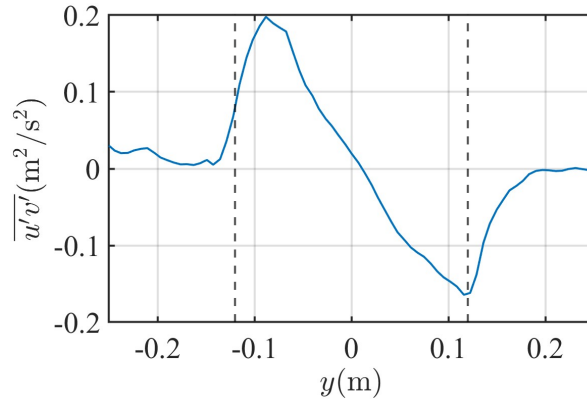


Figure 6.28: The lateral profile of time-averaged shear stress ( $-\overline{u'v'}$ ) averaged across the full-developed region. The dashed line indicate the lateral interfaces of the arrays.

vegetation patch (Rominger & Nepf 2011), the turbulent interaction across the patch produced a wave excursion length over the half width of the patch, leading to an enhancement of lateral transport.

To evaluate the efficiency of horizontal momentum transport across the array interface, the Pearson correlation coefficient,

$$r_{uv} = \frac{u_*^2}{u_{rms}v_{rms}} \quad (6.17)$$

was considered. Figure 6.29b observes that the array expansion improved the efficiency of horizontal momentum transport across the patch interface before the shear layers being confined ( $2b/B < 0.5$ ), presenting a  $r_{uv} \approx 0.5 \sim 0.7$ . In this scenario, the momentum transport was improved as the vortices strength enhanced. However, when the two shear layers met at the channel centerline and flow confinement presented ( $2b/B > 0.5$ ),  $r_{uv}$  approached a constant value  $r_{uv} \approx 0.7$ . Although the vortices were further intensified, the constant  $r_{uv}$  reveals again that the shear layer formed at one array acted like an additional resistance to the shear layer developed at the other array in a vegetation-channel-vegetation system, limiting the momentum transport. In boundary layer flows and canonical mixing layers, typical values of  $r_{uv}$  were  $\approx 0.32$  and  $\approx 0.44$ , respectively (Ghisalberti & Nepf 2002). For partially obstructed channels with emergent complex foliated plants and leafless plants,  $r_{uv}$  were  $\approx 0.6$  and  $\approx 0.4$  respectively (Caroppi et al. 2019). Compared to the  $r_{uv}$  evaluated at a single vortex street, the  $r_{uv} \approx 0.7$  at  $2b/B > 0.5$  in the present experiment indicates that the shear layer-induced confinement highly enhanced the efficiency of momentum transport across the lateral edges of the array.

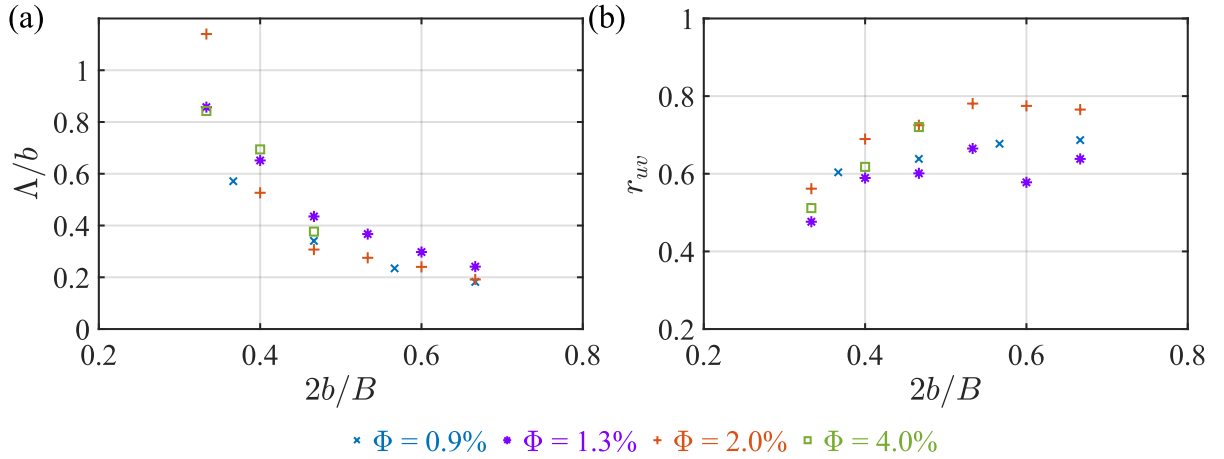


Figure 6.29: The influence of blockage ratio on the momentum exchange across the array interface, evaluated by (a) wave excursion length,  $\Lambda$ , normalized by the array width,  $b$ ; (b) Pearson correlation coefficient,  $r_{uv}$ .

This vegetation-channel-vegetation system generated a lateral flow pattern characterized by slow-fast-slow velocities, which is the reverse of the fast-slow-fast pattern observed in



an in-stream finite vegetation patch. For an in-stream finite vegetation patch with two flow-parallel interfaces separated by the low-speed interior velocity, the vortex interaction across the patch width transported the momentum from the high-discharge side regions towards the low-discharge vegetated region, thereby mitigating the velocity deficit (Rominger & Nepf 2011). This was referred to the formation of a von Karman-like vortex (Zhang et al. 2023). The diminished velocity shear in turn weakened the coherent structures as developing downstream (Zhang, Duan, Yan & Stocchino 2024). However, the vortices in the present experiment interacted across a high-speed region, behaving like a reverse von Karman vortex street (Xu et al. 2017). The high-speed flow in the main central performed like a jet flow, imposing a ‘diverting’ effect toward the side vegetated regions. Concurrently, the plant-induced resistance exerted a constraining impact on this outward diversion. This resistance contributed to sustaining the vortex alterations in the open region. Overall, the spatial structure of the reverse von Karman vortex street is self-sustained under the confined condition while the regular von Karman vortex street is not stable.

## 6.5 Summary

In this chapter, we conducted a laboratory experiment to investigate the flow adjustment, shear layer growth and turbulent interaction within a symmetrical vegetation-channel-vegetation system. A total of 19 configurations of varying patch densities and widths ( $b$ ) were considered for investigation, with the aid of rigorous velocity measurements and dye visualizations.

In the present symmetrical configuration, shear layers initiated at both lateral interfaces of the vegetation array simultaneously grow in the open region. Scaling analysis suggests that, in the outer shear layer, shear stress is primarily balanced by the pressure gradient. When the outer shear layer was fully developed before reaching the channel centerline, the pressure gradient is balanced by bed friction, so that the flow adjustment and shear structure were largely insensitive to the array-to-channel blockage ratio. In this scenario, the fully-developed outer penetration length is given by  $\delta_O \sim h/C_f$ , where  $h$  is the water depth and  $C_f$  is the bed friction coefficient. With constant water depth and bed friction considered in this chapter, a constant outer thickness of  $\delta_O = 0.5(B/2)$  was observed, where  $B$  is the width of the channel, when each array width  $b < 0.5(B/2)$ , corresponding to a blockage ratio of  $2b/B < 0.5$ . As the array extended laterally ( $2b/B > 0.5$ ), flow confinement appears when the outer shear layers penetrate to the channel centerline. The thickness of each outer penetration was then restricted to the half width of the open region,  $\delta_O = B/2 - b$ . In this regime, flow confinement amplifies the pressure gradient, producing a higher interior velocity within the vegetated region and an intensified turbulent structure along the edge, relative to the fully-developed shear layer observed in the present experiment and previous studies. In general, the flow confinement presents when the

full penetration thickness of the outer shear layer is larger than the half width of the open region. However, if water depth or bed friction coefficient varies, the threshold value for flow confinement might change because the full penetration of the outer layer is altered.

Furthermore, within the shear layer, coherent structures were triggered through Kelvin-Helmholtz instability, with a normalized frequency fairly agrees with the normalized natural frequency of mixing layers. Although the shear-layer vortices can self-organize even under confined conditions, increasing the blockage ratio from 0.33 to 0.67 led to an increase in vortex frequency by over 100%, a reduction in momentum thickness by approximately 60%, and an increase in convection velocity by about 40%. The time-averaged shear stress was zero at the centerline when the shear layer was confined to one half of the open region, but the shear-layer vortices interacted across the open region, observing significant but equally-contributing turbulent events from both sides. Furthermore, a wavy interface was visualized by dyes released at two side edges, revealing a wave motion with a phase shift of  $\pi$  radians between the parallel vortex streets. The alternating low-pressure vortex cores between the parallel vortex streets amplify the pressure gradient, intensifying coherent structures and facilitating momentum exchange across the channel centerline. While the turbulent intensity improves, the decrease in resident time for the turbulent flow events may lead to shorter transport distances, from  $0.8b$  to  $0.2b$ . Consequently, the shear layer developed on one interface acts as an extra resistance to shear turbulence on the opposite interface. From the perspective of vegetation restoration and management in natural channels or urban drainage systems, the width of the vegetation array should be carefully considered to minimize flow confinement effect. Intense flow confinement can enhance velocity within vegetated zones and elevate turbulence at the patch edges, which may reduce sediment retention within the patch and promote erosion along the patch boundaries.

This work applied two-dimensional Particle Image Velocimetry (PIV) analysis to examine the flow evolution and turbulent structure at the water surface. Compared with the point-by-point data measured at the middle of water depth using ADV, both the streamwise and transverse integral time scales of the coherent structures were greater at the water surface, but their ratio remained constant, revealing that although the vortices increased in size near the water surface, their overall shape did not change. PIV analysis improved the understanding of the wave motion created by the self-organization of the parallel vortex streets. The formation of the wave motion highly enhanced the turbulence in the open region, concentrating on the strain-dominated regions, which is distinct from the single shear layer observed at the lateral edge of partially vegetated channels or at the top interface of submerged canopies, where the peak turbulent kinetic energy aligned with the inflection point of the shear layer.

To make our conclusions more applicable to different scenarios, further investigation into the characteristics of the array is necessary, as factors such as stem size, stem alignment, flexibil-

ity, degree of submergence and surface area (skin friction) can significantly influence patch hydraulic resistance, velocity shear, and vortex structure. Additionally, a wider range of hydraulic conditions should be considered, since variables like water depth and bed friction coefficient can also impact the development of shear layers in open region.

# Chapter 7

## The interaction between the patch-scale coherent structures associated with a rectangular array of emergent vegetation and bedform development

### 7.1 Introduction

While previous Chapters have described some aspects of flow and turbulence within and adjacent to porous, emergent structures, many aspects of patch-flow-morphology feedback still require investigation to enable prediction of sediment loss and accretion from finite patches of emergent vegetation and porous structures designed to mitigate erosion. The present chapter considered the morphological response to an in-stream rectangular patch of emergent cylinders, focusing on the role of vortices formed along the patch flow-parallel edges and in the wake as agents of sediment transport.

### 7.2 Methods

The experiments were designed to compare the morphological response to a dense patch, for which sediment supply may be limited in the interior of the patch, to the response to a sparse patch, for which KH vortices were expected to penetrate the patch and provide supply into the patch. To achieve this comparison, the patch geometry was chosen based on the non-dimensional flow-blockage  $C_{Dab}$  greater and less than 2, as defined in Rominger & Nepf (2011). Specifically,  $C_{Dab} = 0.91$  and  $C_{Dab} = 3.88$ , were chosen to represent low and high flow blockage, respectively.  $C_D$  is the drag coefficient of the array elements,  $C_D = 1$  was assumed for

simplicity (Rominger & Nepf 2011),  $a$  ( $= 4.9$  and  $19.7\text{m}^{-1}$ ) is the frontal area per volume within the array, and  $b$  ( $= 18.3$  and  $19.7$  cm) is the half-width of the array. The array length was  $L = 2.65$  m based on preliminary tests to ensure the full development of KH vortices. The array parameters are summarized in Table 7.1.

The origin of the Cartesian coordinate system ( $x = 0, y = 0$ ) was placed at the leading edge of the array and at the mid-point of the array and channel, respectively, with  $x$  positive in the streamwise direction (Figure 7.1a). The velocity components were denoted as  $(u, v)$  in the  $(x, y)$  directions, respectively. Velocity was collected along the channel centerline, along the flow-parallel edge of the array, and along multiple lateral transects within and downstream of the array (red dashed lines in Figure 7.1).

Details related to hydraulic condition and sediment characteristics (Chapter 3.3), model plant (Chapter 3.4), data collection (Chapter 3.5), data treatment (Chapter 3.6), dye tests (Chapter 3.7) are included in Chapter 3.

For further analysis, the change in bed elevation before and after exposure to flow is defined as the net deposition,  $\delta_b$ . The length of the scour region measured from the patch leading edge is defined as the scouring length,  $L_s$ . The length of the depositional dune measured from the end of scouring region  $x = L_s$  refers to  $L_d$ . By integrating the net deposition  $\delta_b$  across the scour region ( $x = 0$  to  $L_s$ ) within the patch ( $y = 0$  to  $b$ ), the volume of erosion at the leading edge of the patch is  $V_e = \int_0^{L_s} \int_0^b \delta_b dy dx$ . The volume of the deposition mound inside the patch was quantified by integrating the net deposition  $\delta_b$  between  $x = L_s$  to  $L_s + L_d$  and  $y = 0$  to  $b$ , i.e.,  $V_d = \int_{L_s}^{L_s+L_d} \int_0^b \delta_b dy dx$ . Using the water surface as reference, the local water depth was defined as the difference between the water surface and local bed elevation.

| $b$<br>(cm) | $\Phi$ | $N$<br>( $\text{m}^{-2}$ ) | $a$<br>( $\text{m}^{-1}$ ) | $L_i$<br>(m) | $L_{i,c}$<br>(m) | $L_s$<br>(m)  | $L_d$<br>(m)  | $h_s$<br>(cm) | $h_d$<br>(cm) | $V_e$<br>( $\text{cm}^3$ ) | $V_d$<br>( $\text{cm}^3$ ) |
|-------------|--------|----------------------------|----------------------------|--------------|------------------|---------------|---------------|---------------|---------------|----------------------------|----------------------------|
| 19.7        | 19.6%  | 1550                       | 19.7                       | 0.9          | 1.4<br>(0.1)     | 0.20<br>(0.1) | 0.36<br>(0.1) | -2.8<br>(0.1) | 1.6<br>(0.1)  | 1150<br>(110)              | 270<br>(30)                |
| 18.3        | 4.9%   | 388                        | 4.9                        | -            | 2.2<br>(0.2)     | 0.39<br>(0.1) | 0.56<br>(0.1) | -6.3<br>(0.1) | 4.5<br>(0.1)  | 3240<br>(30)               | 1780<br>(20)               |

Table 7.1: Summary of experimental parameters. Bracketed numbers indicate uncertainty.  $L_i$  is the measured interior adjustment length.  $L_{i,c}$  is the calculated interior adjustment length, Eq. 3.23.  $L_s$  is the length of the scour region measured from the patch leading edge, and  $h_s$  is the depth of the scour.  $L_d$  and  $h_d$  are the length and height of the depositional dune within the patch.  $V_e$  is the volume of erosion at the leading edge of the patch.  $V_d$  is the volume of the deposition mound inside the patch.

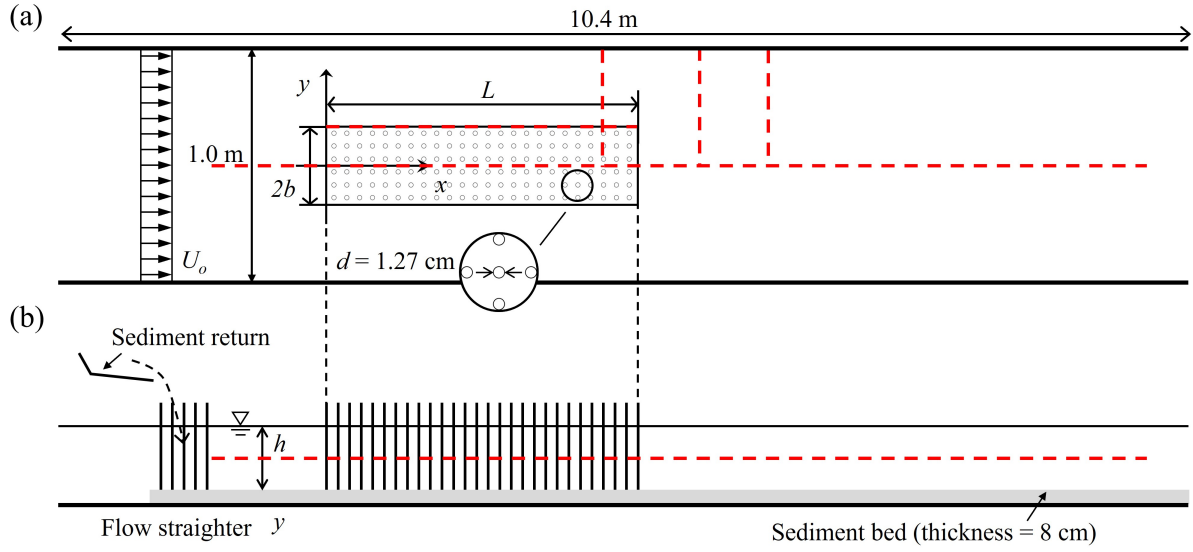


Figure 7.1: Experiment setup. (a) Top view. (b) Side view. Not to scale. The longitudinal and transverse coordinates and velocity are  $(x, y)$  and  $(u, v)$ , respectively. Red dashed lines indicate measurement transects, including the centerline, the flow-parallel edge, and several lateral cross-sections.

## 7.3 Results

The change in the velocity field and introduction of new turbulence structures in response to the rectangular patch are discussed first, and these changes in flow field are related to morphological changes. After this, the feedback from morphological changes to the velocity structure is analyzed.

### 7.3.1 Velocity and bedform evolution through the patch

Starting at the leading edge ( $x = 0$ ), velocity within the patch decelerated over the interior adjustment length,  $L_i$ , and then reached a nearly constant value (Figure 7.2a, b). Theory and scaling over a flat bed predict Equation. 3.23. However, in this experiment, the bed did not remain flat. In particular, significant scour and deposition occurred near the leading edge (Figure 7.2c, d). The presence of bedforms shortened the adjustment length, relative to Eq. 3.23. Specifically, for the high flow blockage patch,  $C_{Dab} = 3.88$ , Eq. 3.23 predicted  $L_{i,c} = 138 \pm 8$  cm, but, the measured adjustment length was  $L_i = 90 \pm 10$  cm (Figure 7.2a). For the sparse patch (Figure 7.2b),  $L_i = 198 \pm 10$  cm was measured for the initially flat bed, which agreed with Eq. 3.23,  $L_{i,c} = 220 \pm 20$  cm. However, after the bedform developed,  $L_i$  was reduced to  $146 \pm 10$  cm. The shortened adjustment length was attributed to the deformation of the bed near the patch leading edge (Figure 7.2c). This finding aligned with the numerical model of a

near-bank vegetation patch described in Yi et al. (2022), who also attributed a shortened interior adjustment length to bed deformation near the leading edge of the patch.

While the velocity within the patch declined monotonically from the leading edge, the turbulence was locally elevated, compared to the bare bed upstream of the array. Specifically, for the dense patch, turbulence was enhanced between  $x = 0$  to 60 cm, relative to the bare bed region upstream of the patch, and then decayed to  $k_t = 2.3 \pm 0.4 \times 10^{-4} \text{m}^2/\text{s}^2$  for  $x > L_i$  (blue symbols, Figure 7.2a). The turbulence enhancement came from turbulence generated by stems within the array. Stem-scale turbulence is generated if stem Reynolds number  $Re_d = \bar{u}d/\nu > \approx 100$  (Liu & Nepf 2016), and  $Re_d > 400$  over the entire array, so stem-scale turbulence was present within the array.

A region of scour began just upstream of the patch and extended into the patch over the sediment adjustment length-scale,  $L_s = 20 \text{ cm} < L_i$  (Figure 7.2c), indicating that the mean velocity and turbulence intensity dropped below the threshold for sediment motion before the velocity was fully developed. This highlights how the morphological response depended on the substrate characteristics, which set the critical velocity and turbulence at which sediment motion can be initiated. Specifically, sediment mobility is dependent on grain size. For  $d_{50} = 0.35 \text{ mm}$ , used in the present work, the critical velocity was  $U_c = 0.22 \text{ m/s}$ , and the critical turbulence was  $k_{t,c} = 1.2 \times 10^{-3} \text{m}^2/\text{s}^2$ , as described in the Methods. The measured velocity and turbulent kinetic energy in the fully adjusted region ( $x > L_i$ ) were lower than these critical values (Figure 7.2a), and consistent with this, no sediment erosion was detected in this region (Figure 7.2c).

Figure 7.3 illustrates the spatial pattern of erosion (blue) and deposition (red) within and around both the high and low flow-blockage patches. Erosion (blue) was most significant within a horseshoe-shaped region at and adjacent to the leading edge of the patch. A similar pattern of erosion was observed around the leading edge of a circular patch (Follett & Nepf 2018) and at the leading edge of a rectangular patch adjacent to a channel wall (Kim, Kimura & Shimizu 2015). A fraction of the sediment eroded at the leading edge was carried into the patch, creating a deposition dune within the patch (red color at  $x = 20$  to 56 cm and 39 to 95 cm, for the high and low flow blockage patches, respectively, Figure 7.3). In both patches, the volume of sediment eroded at the leading edge ( $V_e$ ) was larger than the volume deposited within the patch near the leading edge ( $V_d$ , see Table 7.1), indicating that only a fraction of sediment eroded at the leading edge was carried into and deposited within the patch ( $V_d/V_e = 24\%$  and  $55\%$  for the high and low flow blockage patches, respectively). A similar deposition mound inside the leading edge has been observed in finite patches along a side wall (Kim, Kimura & Shimizu 2015) and in submerged patches which cover the full width of the flume (Chen, Chan & Li 2012, Le Bouteiller & Venditti 2014, Tinoco & Coco 2016). In the previous cases, the volume of scour and deposition inside the patch increased with decreasing array density, which was attributed to the higher velocity and turbulence inside the patch at the leading edge. Consistent with these

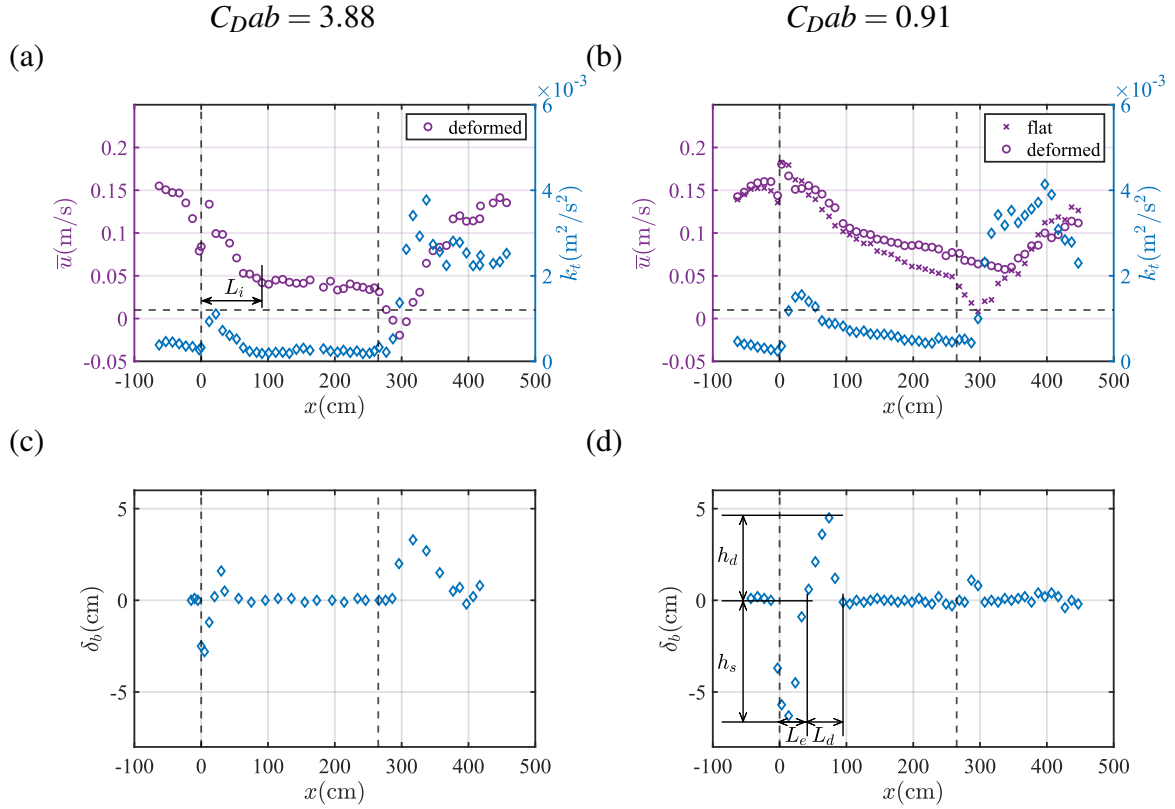


Figure 7.2: Longitudinal profiles of (a, b) time-averaged streamwise velocity ( $\bar{u}$ ) and turbulent kinetic energy ( $k_t$ ), and (c, d) bed elevation ( $\delta_b$ ) for high flow blockage patch and low flow blockage patch, respectively. The data collected on the centerline ( $y = 0$ ). Vertical dashed lines indicate the leading ( $x = 0$ ) and trailing ( $x = L$ ) edges of the array. In (a) and (b), the horizontal dashed line indicates the estimated critical turbulence level for sediment mobility.



previous observations, in our experiment the velocity inside the low flow blockage patch was higher (Figure 7.2) and resulted in larger scour and deposition ( $V_e$ ,  $V_d$  in Table 7.1, Figure 7.2c, d). Finally, along the centerline of the patch, scour and deposition were absent downstream of the deposition mound (zero net deposition Figure 7.2c and 7.2d), indicating that there was no supply of sediment to this region or erosion within this region. This was consistent with the fact that both the velocity and turbulence within this region were below the mobilization thresholds (Figure 7.2a and 7.2b).

Near the leading edge, erosion and deposition within the patch varied mostly in the stream-wise direction and was approximately uniform across the patch width (Figure 7.3). However, downstream of the adjustment region ( $x > L_i$ ), the erosion and deposition pattern varied laterally across the patch width. Specifically, for the high-density patch, a flow-parallel depositional ridge was generated in the region  $x > L_i = 90$  cm and just inside flow-parallel edge (red region along patch edge, Figure 7.3a). In contrast, a depositional ridge did not form along the flow parallel edge for the low-density patch (Figure 7.3b). This difference was not associated with lateral transport at the patch edge. Specifically, in the region of fully-adjusted flow, the time-mean lateral velocity ( $\bar{v}$ ) at the patch edge was negligible for both patches (Figure 7.4a), as expected for  $d\bar{u}/dx = 0$  (Figure 7.2a), and thus the time-averaged velocity field cannot explain the difference in bed morphology between the two patches. The oscillating component of lateral velocity ( $v_{rms}$ ) along the patch edge was also similar between the two patches (Figure 7.4b). Thus, the difference in flow-parallel ridge formation was most likely due to the difference in time-averaged streamwise velocity and turbulence within the patch, both of which were higher for the low flow blockage patch (Figure 7.4c and 7.5d). The formation of the flow-parallel ridge is discussed in more detail in the next section.

Finally, for the low flow blockage patch, deposition within the patch was observed very close to the end of the patch (Figure 7.3b, red regions between  $x = 210$  to  $265$  cm), which was likely due to flow recirculation in the lee of the patch. Although negative velocity was not observed at the centerline, the velocity did go to zero downstream of the patch (Figure 7.2b). To confirm that the ridges were associated with the trailing edge of the patch, we extended the patch to  $L = 385$  cm, and the position of the deposition region moved downstream, again associated with the trailing edge (Figure 7.2c). Finally, all sediment eroded within and adjacent to the patch was transported downstream, depositing in a finite length wake region, producing a V-shaped depositional mound after the patch (Figure 7.3a and 7.3b). Because no sediment collected in the sediment trap, we concluded that no sediment was transported beyond  $x = 480$  cm. That is, while the patch generated a significant local redistribution of sediment, extending over  $1.8L$ , it did not produce channel scale transport. A similar local redistribution of sediment was also observed in Follett & Nepf (2012).

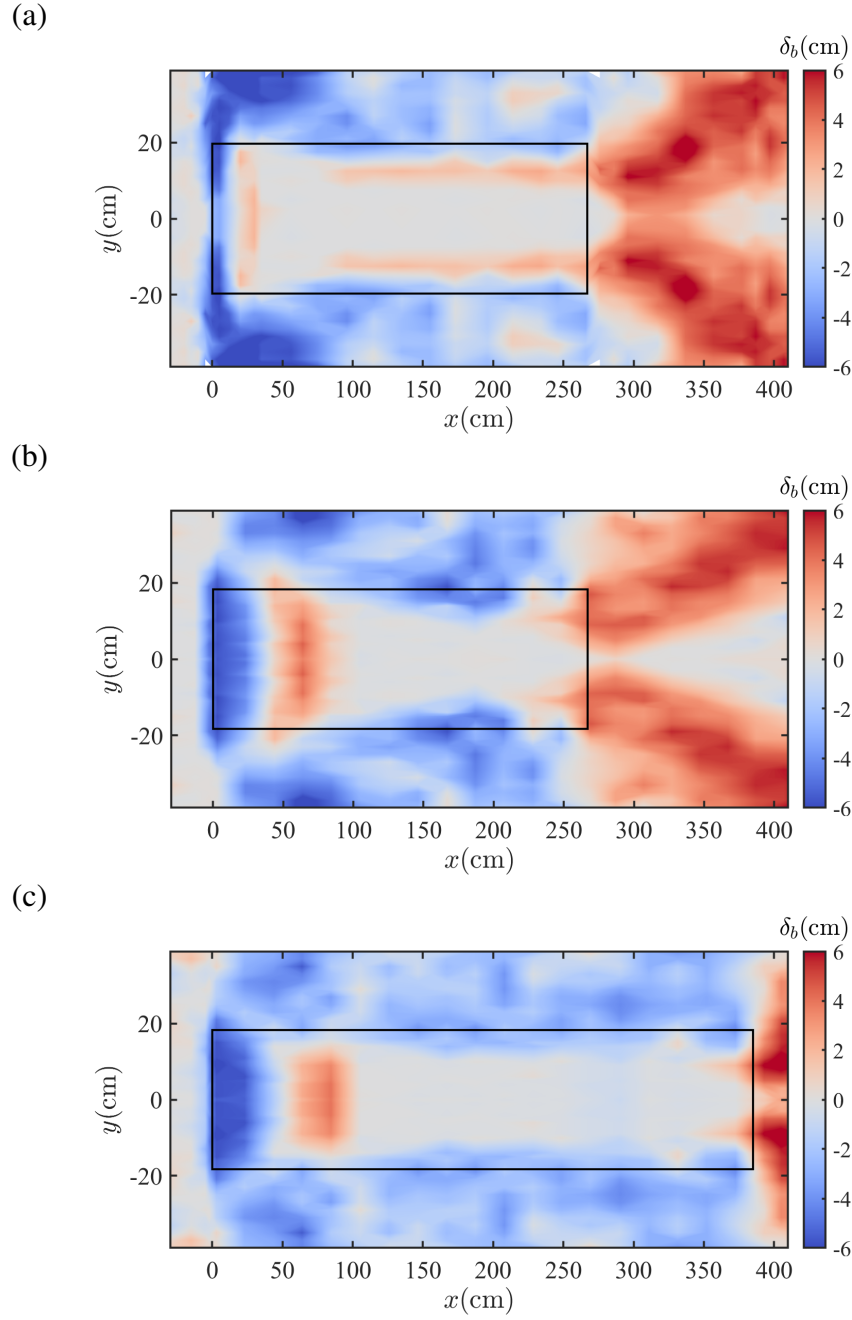


Figure 7.3: Net deposition ( $\delta_b$ ) for the (a) high flow blockage patch ( $C_{Dab} = 3.88$ ) with a length of  $L = 265$  cm, (b) low flow blockage patch ( $C_{Dab} = 0.91$ ) with a length of  $L = 265$  cm and (c) extended low flow blockage patch ( $C_{Dab} = 0.91$ ) with a length of  $L = 385$  cm. Grey indicates zero net deposition; red indicates positive net deposition; blue indicates negative net deposition (net erosion). The solid rectangle indicates the limits of the array.

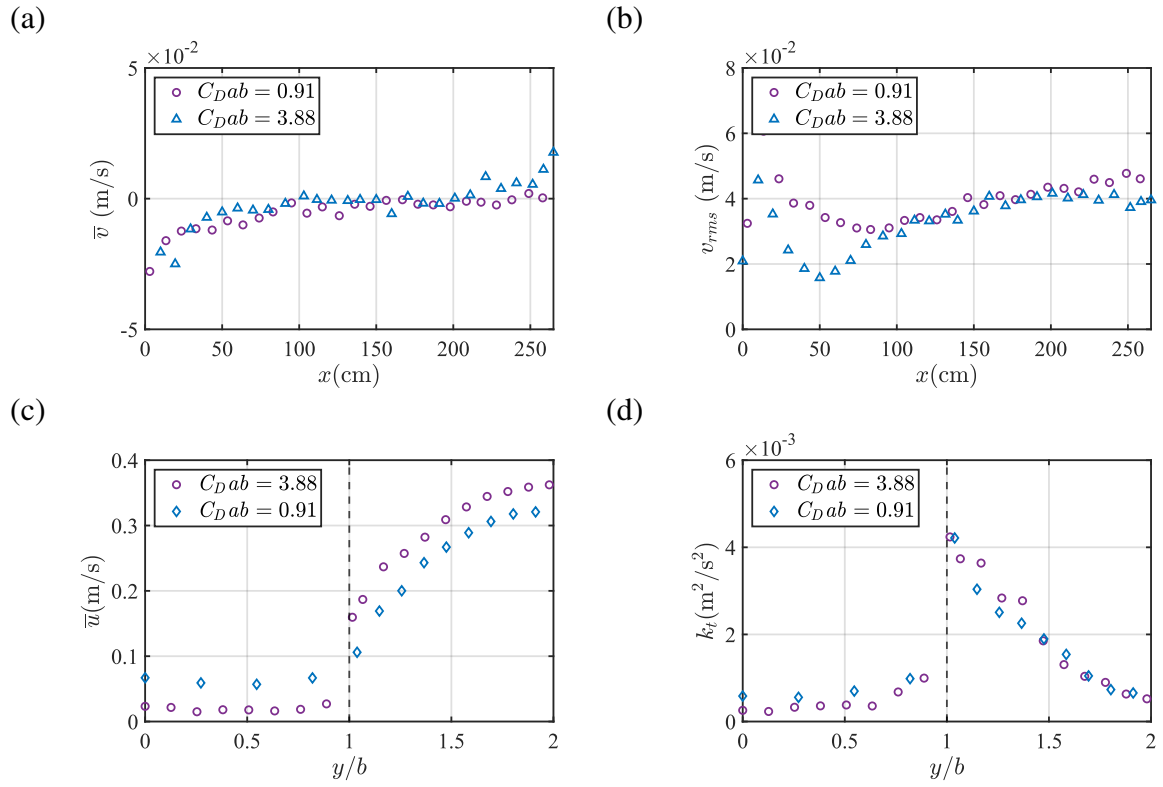


Figure 7.4: Longitudinal profiles along the flow-parallel edge at  $y = b$ : (a) time-averaged spanwise velocity ( $\bar{v}$ ) and (b) fluctuating spanwise velocity ( $v_{rms}$ ). Lateral profiles of (c) time-averaged streamwise velocity ( $\bar{u}$ ) and (d) turbulent kinetic energy ( $k_t$ ) in the fully developed region ( $x > L_i$ ).

### 7.3.2 The formation of the flow parallel depositional ridge deposition

For the high flow blockage patch, a flow-parallel depositional ridge formed just inside flow-parallel edge in the fully developed region ( $x > L_i$ , Figure 7.3a). The formation and position of the ridge was associated with the shear layer along the patch edge. Flow diversion away from the high drag within the patch created a velocity difference (Figure 7.5a) between the free stream adjacent to the patch ( $y > b$ ) and the patch interior ( $y < b$ ), which contributed to the formation of coherent structures by Kelvin-Helmholtz instability. The vortices penetrated the vegetated region over distance  $\delta_I$ , and grew into the free stream region over distance  $\delta_O$ . The power spectral density (PSD) of the transverse velocity ( $v$ ) indicated a dominant frequency close to that predicted for KH instability,  $f_{KH}\theta/\bar{U} = 0.032$  (Ho & Huerre 1984) (Figure 7.5b). However, based on the lateral profile of streamwise velocity and shear stress (Figure 7.5a), the KH structures and associated turbulent transport did not penetrate into the patch beyond the first row of dowels. Specifically,  $\delta_I$  was smaller than 2.5 cm, which was the distance from the patch edge to the first measurement point within the array. Note that the depositional ridge formed farther into the patch, between 7.5 cm and 12.5 cm from the patch edge, such that transport associated with shear-layer turbulence cannot explain the extent of cross-stream sediment transport needed to form the ridge.

A second mechanism of cross-stream transport likely contributed to the formation of the depositional ridge, associated with the wave motion induced by the passage of the vortices along the patch edge (White & Nepf 2007, Zong & Nepf 2011). Specifically, the center of each KH vortex is a point of low pressure, whose passage along the patch edge generates an oscillating response within the array (White & Nepf 2007). Necessarily, the frequency of the vortex-induced wave response is the same as the vortex passage, so that peaks in the PSD of the cross-stream velocity were consistent across the patch width (Figure 7.5b). The wave response was apparent in the velocity records. Specifically, within the patch interior, there was a phase shift of  $\pi/2$  radians between the streamwise velocity ( $u$ ) and transverse velocity ( $v$ ), consistent with a wave motion (Figure 7.5d, 7.6e). In contrast, within the shear layer (e.g., 1 cm outside the patch)  $u$  and  $v$  were anticorrelated, consistent with the higher Reynolds stress of the shear layer.

Lateral transport associated with the wave response likely contributed to the formation and location of depositional ridge inside the dense patch ( $y = b - \delta_s$ ). Similarly, Zong & Nepf (2011) showed that the vortex-induced wave response along a patch edge contributed to the delivery and deposition of suspended material within the patch, allowing sediment to be delivered to regions inside the patch not directly accessible by turbulent flux. Note that the lateral position of the ridge was constant over the length of the patch (Figure 7.3a), which was consistent with the uniform wave response ( $v_{rms}$ , Figure 7.4b) along the patch edge. A weaker wave motion in the central region of the vegetation patch (Figure 7.5) restricted the delivery of sediment

to the patch centerline. Consequently, despite the reduction in turbulence and velocity in this area ( $x > L_s + L_d$ ,  $-7.5 \text{ cm} < y < 7.5 \text{ cm}$ , Figure 7.5a, Figure 7.5e), no sediment deposition occurred.

Elevated turbulence and velocity near the streamwise edge of the patch produced erosion (blue, Figure 7.3). For the dense patch, the erosion extended over the distance  $\delta_e = 5.0 \pm 1.3 \text{ cm}$  into the patch, which was consistent with the region of elevated turbulent kinetic energy (Figure 7.5e). However, in the fully-developed region, the net deposition averaged across the dense patch width was zero within uncertainty ( $\frac{1}{b} \int_0^b \delta_b dy = 0.8 \pm 0.8 \text{ mm}$ ), indicating that the depositional ridge inside the patch was created from sediment eroded at the interfaces, and did not represent new sediment arriving from outside the patch (Figure 7.6). In contrast, for the sparse patch,  $\frac{1}{b} \int_0^b \delta_b dy = -7.2 \pm 0.3 \text{ mm}$  reveals a net loss of sediment from the patch. In this case, material eroded near the edge was carried out of the patch.

Finally, outside the patch ( $y > b$ ), elevated turbulence and velocity produced significant scour (Figure 7.5e). Although the velocity was higher outside the shear layer ( $y > b + \delta_o$ ) (Figure 7.5b), the scouring was more significant directly adjacent to the array ( $y < b + \delta_o$ ). In fact, the velocity in the patch-adjacent region was lower than the critical velocity for sediment motion on bare bed,  $\bar{u} < U_c = 0.22 \text{ m/s}$ . However, the turbulence adjacent to the patch was above the critical magnitude,  $k_t > k_{t,c} = 1.2 \times 10^{-3} \text{ m}^2/\text{s}^2$ , over the region  $y = 17 \text{ cm}$  to  $32 \text{ cm}$ , consistent with region of scour ( $\delta_b < 0$ , Figure 7.6e), indicating that the elevated turbulence was triggering the erosion at the patch edge.

### 7.3.3 The influence of stem diameter on interfacial shear layer

For both patch densities ( $C_{Da} = 4.9$  and  $19.7 \text{ m}^{-1}$ ), the shear layer at the patch lateral edge has a limited extension into the array. Specifically, the inner penetration length  $\delta_l < 2.5 \text{ cm}$  (Figure 7.5a, Figure 7.7a). The dowel diameter was  $d = 1.27 \text{ cm}$ , similar to  $\delta_l$ , suggesting that the KH vortices and associated shear-layer did not penetrate past the first row of the dowels. This stands in sharp contrast to previous studies of rectangular patches constructed with a smaller dowel diameter,  $d = 0.64 \text{ cm}$ , but the same range of  $C_{Da}$ , which exhibited a strong dependence between  $\delta_l$  and  $C_{Da}$ . Specifically, Rominger & Nepf (2011) observed that  $\delta_l$  decreased from  $10 \text{ cm}$  to  $2 \text{ cm}$  when  $C_{Da}$  increased from  $5.3 \text{ m}^{-1}$  to  $20 \text{ m}^{-1}$ , which was consistent with the theoretical and empirical formula given in White & Nepf (2008),  $\delta_l = \max[0.5(C_{Da})^{-1}, 1.8d] = 9.5 \text{ cm}$  and  $2.5 \text{ cm}$ , respectively. The limited penetration of the shear layer in the present experiment was likely due to the locally stronger shear created by the larger and in-line dowels, compared to the smaller and staggered arrangement used in previous studies. Specifically, the locally intense shear generated by the in-line wakes of dowels along the edge of the patch produced shear-sheltering, which blocked the penetration of the KH vortices into the patch (Ptasinski et al. 2003, Hunt & Durbin 1999).

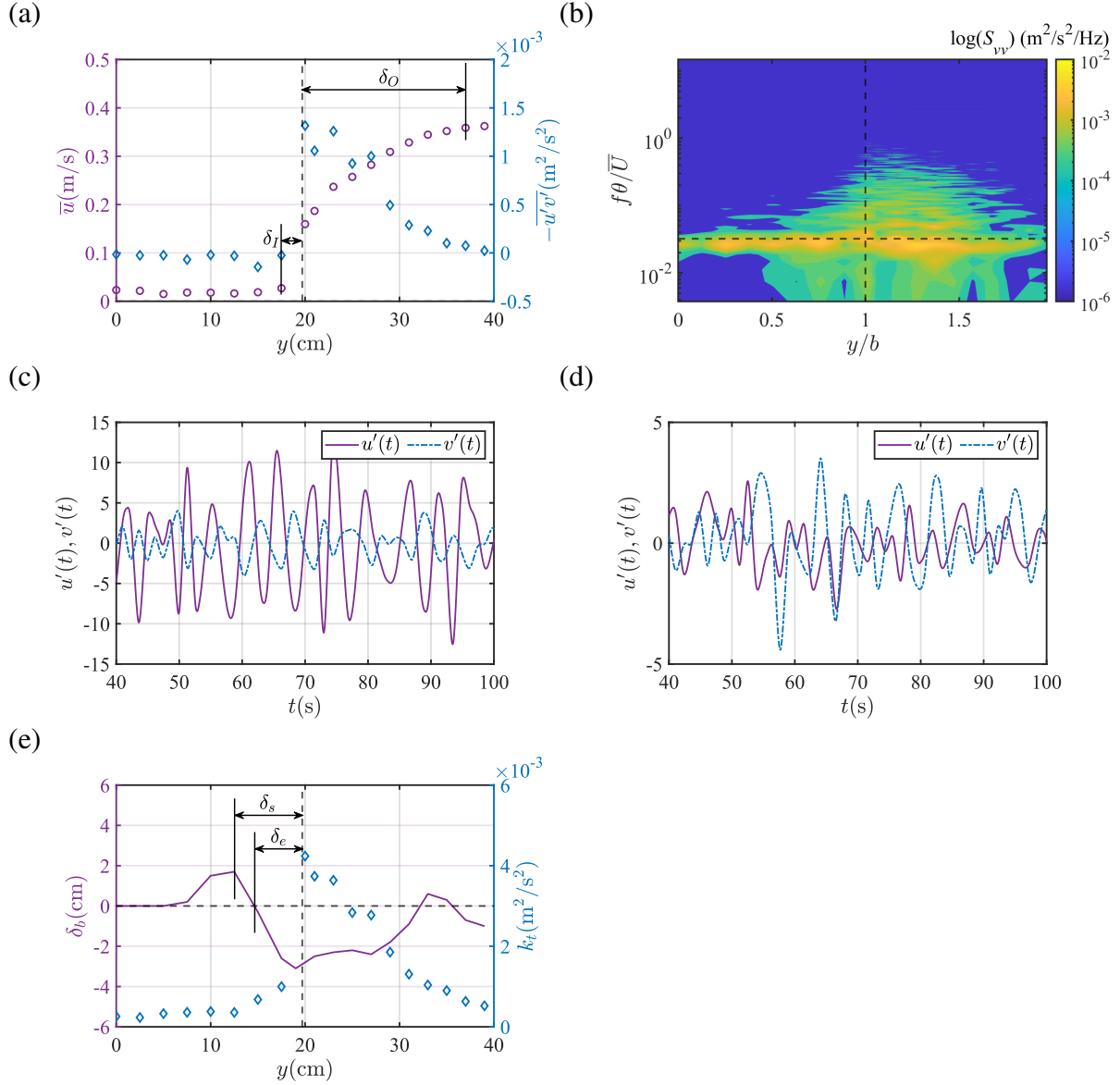


Figure 7.5: Conditions contributing to the formation of edge-parallel ridge within the fully developed region ( $x > L_i$ ) of the high flow blockage patch ( $C_{Dab} = 3.88$ ). (a) Lateral profiles of time-averaged streamwise velocity ( $\bar{u}$ ) and Reynolds shear stress ( $-\overline{u'v'}$ ). (b) Magnitude of power spectral density (PSD) of cross-stream velocity ( $v$ ), shown by color bar, distributed by lateral position and frequency. The horizontal dashed line indicates expected Kelvin-Helmholtz frequency,  $f_{KH}\theta/\bar{U} = 0.032$ . The time series of fluctuating streamwise ( $u'(t)$ ) and transverse ( $v'(t)$ ) velocity (c) at 1 cm outside the patch and (d) within the patch ( $y = b - \delta_s$ ). (f) Lateral profiles of bed elevation ( $\delta_b$ ) and turbulent kinetic energy ( $k_t$ ). The horizontal black dashed line indicates the initial bed elevation,  $\delta_b = 0$ . The vertical dashed line indicates the lateral interface of the array ( $y = b$ ).

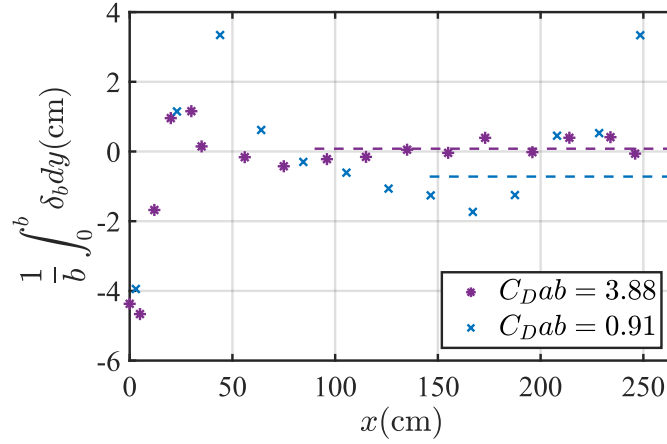


Figure 7.6: The laterally averaged net deposition  $\frac{1}{b} \int_0^b \delta_b dy$  at each streamwise position along the array. The dashed horizontal line represents the average value in the fully developed region ( $x > L_i$ ).

Further, for patches constructed with smaller dowels (e.g., Rominger & Nepf (2011)), the KH vortices along the two flow-parallel interfaces interacted across the patch width when  $C_{Dab} < 2$ , and this enhanced the Reynolds stress. However, this interaction was not observed for the low flow-blockage patch ( $C_{Dab} = 0.91$ ) in the present experiment. Specifically, we compared the lateral distribution of Reynolds stress and  $v_{rms}$  between scenarios in which the vortices were able to communicate across the patch, and scenarios in which this communication was blocked by a splitter plate placed at the patch centerline. The lateral profile of  $-\overline{u'v'}$  and  $v_{rms}$  with and without a splitter plate were nearly identical (Figure 7.7), with a 10% and 20% change only at the peak values for  $v_{rms}$  and  $-\overline{u'v'}$ , respectively. This was a much smaller change than the 35% and 85% reductions, respectively, observed with the additional of centerline plate in Rominger & Nepf (2011). This comparison suggested that vortex synchronization across the patch width did not occur in the present experiment. This was likely due to the restriction of KH penetration into the patch by shear-sheltering. This is a key new result that indicates how patch velocity structure can be influenced by the size and arrangement of the elements within the patch.

### 7.3.4 Deposition in the patch wakes

Directly downstream of the high-flow blockage patch, the side-parallel depositional ridges ( $y = b \pm \delta_s$ ) grew towards the centerline, enclosing a region of no bed elevation change (grey color in Figure 7.3) between  $x = 270$  to  $290$  cm. Even though flow conditions within this zone were favorable for deposition, with  $\bar{u} < U_c$  and  $k_t < k_{t,c}$ , no sediment was supplied by bedload to this region, and thus net deposition was zero. However, this region did accumulate the fine

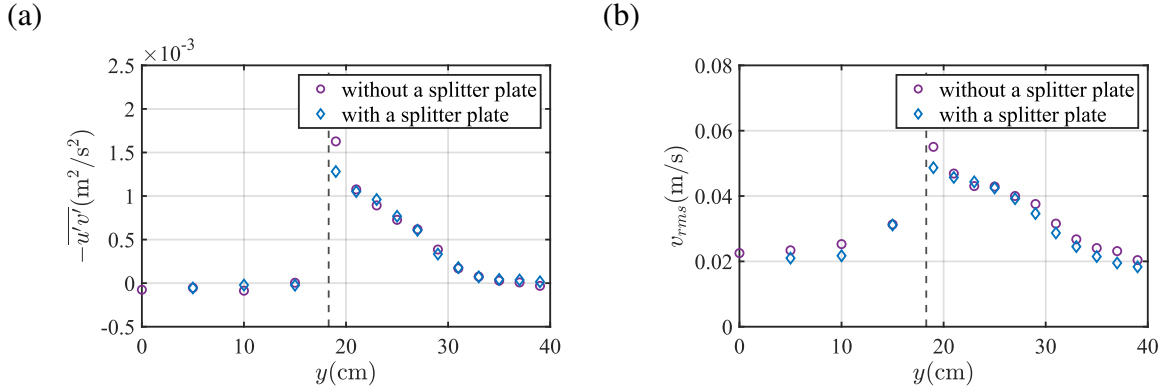


Figure 7.7: The lateral profiles of (a) Reynolds shear stress ( $-\overline{u'v'}$ ) and (b) fluctuating spanwise velocity ( $v_{rms}$ ) for low-density patch with and without a splitter plate at the patch centerline. The dashed lines indicate the lateral interface of the patch,  $y = b$ .

suspended material present in the flume (residual rust particles), which was evident by the change in surface color from sand to reddish brown (Figure 7.11). A similar region of zero net deposition was observed directly downstream of a rectangular patch located along a side wall (Kim, Kimura & Shimizu 2015), and a high flow blockage circular patch (Follett & Nepf 2012). Further, Follett & Nepf (2012) also observed the accumulation of suspended sediment in this region.

Farther downstream from a patch, the sediment scoured from around the patch was deposited, which was also observed in previous studies (e.g., Follett & Nepf (2012), Kim, Kimura & Shimizu (2015)). However, the spatial distribution of net deposition in the wake of a structure is dependent on local sediment transport capacity, dictated by velocity and turbulence, and also on the sediment characteristics (Okhravi et al. 2023). For example, downstream of Follett & Nepf (2012)'s high flow-blockage circular patch deposition occurred on the centerline, whereas in the wake of the rectangular patch in this experiment, deposition was mostly distributed away from the centerline. In Follett & Nepf (2012)'s case, a strong von Karman vortex street was present in the patch wake and carried material eroded around the patch toward the centerline, which is similar to the mechanism producing a depositional mound on the centerline behind a solid circular obstruction (Dargahi 1990, Yagci et al. 2017). In this experiment, net deposition did not peak at the centerline, but peaked at a point 8.7 cm inward from the patch edge (darkest red downstream of patch in Figure 7.3a), which was less than the wake half-width. This suggested that the lateral transport in the wake was less than the half width of the patch. For the dense patch, the fluctuating transverse velocity in the wake was  $v_{rms} = 6.9$  cm/s (Figure 7.8), with frequency of  $f_{VK} = 0.16$  Hz. The lateral transport associated with this motion would be  $\Lambda = \sqrt{2}v_{rms}/2\pi f_{VK} = 9.7$  cm, which was less than the patch half-width  $b = 19.7$  cm. The stronger lateral oscillation, indicated by higher  $v_{rms}$  (Figure 7.8), in the wake of the high-flow



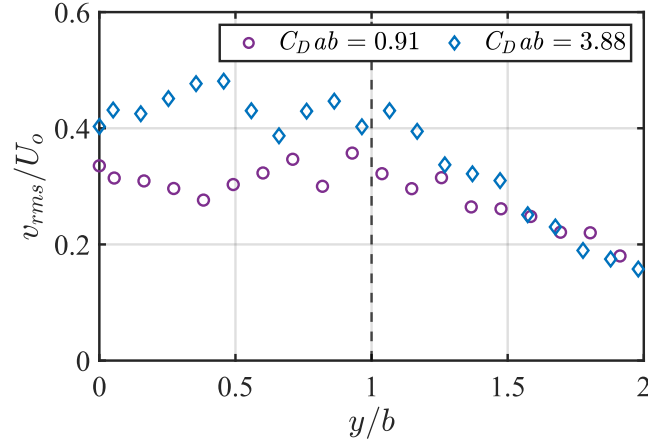


Figure 7.8: Lateral profiles of normalized fluctuating cross-stream velocity ( $v_{rms}/U_o$ ) at  $x = 318$  cm and 328 cm, i.e., 50 cm and 60 cm after the trailing edge of the high flow blockage patch and low flow blockage patch, respectively. The dashed line indicates the half width of the patch,  $y = b$ .

blockage patch resulted deposition transported further inward to the centerline, when compared to the low-flow blockage patch (Figure 7.3). Specifically, the distance from the side edge of the patch to the position where the depositional mound peaked was 8.7 cm and 7.3 cm for the dense and sparse patch, respectively.

Farther downstream from the patch, the V-shaped mound widens (Figure 7.3). This expanding, V-shaped deposition pattern was also observed in a low flow blockage circular patch (Follett & Nepf 2012, Yagci et al. 2017) and a square array (Kim, Nabi, Kimura & Shimizu 2015), and was attributed to the absence of, or weakness of the wake vortex (Follett & Nepf 2012). Specifically, the lateral velocity needed to carry the sediment to the centerline was absent or too weak. Note that, we do not believe the deposition pattern in the present experiment was linked to the ratio of array width to channel width (40% in the present experiment), because the same pattern of separated deposition mounds was also present when the patch diameter to channel width was less than 18% (Follett & Nepf 2012).

### 7.3.5 Feedback from morphological evolution to wake velocity structure

To illustrate how the evolution of the bed morphology altered the flow structure, conditions with the initial, flat bed ( $t = 0$ ) and with fully-developed bedforms ( $t = 96$  hr) are compared in Figure 7.9. First, erosion adjacent to the patch (Figure 7.3) increased the local flow depth by 3 cm and generated bedforms with an amplitude of 2 cm. The increase in flow depth tended to decrease the flow resistance, but the introduction of bedforms tended to increase it. These competing affects appeared to balance in the present experiment, as the distribution of velocity between the

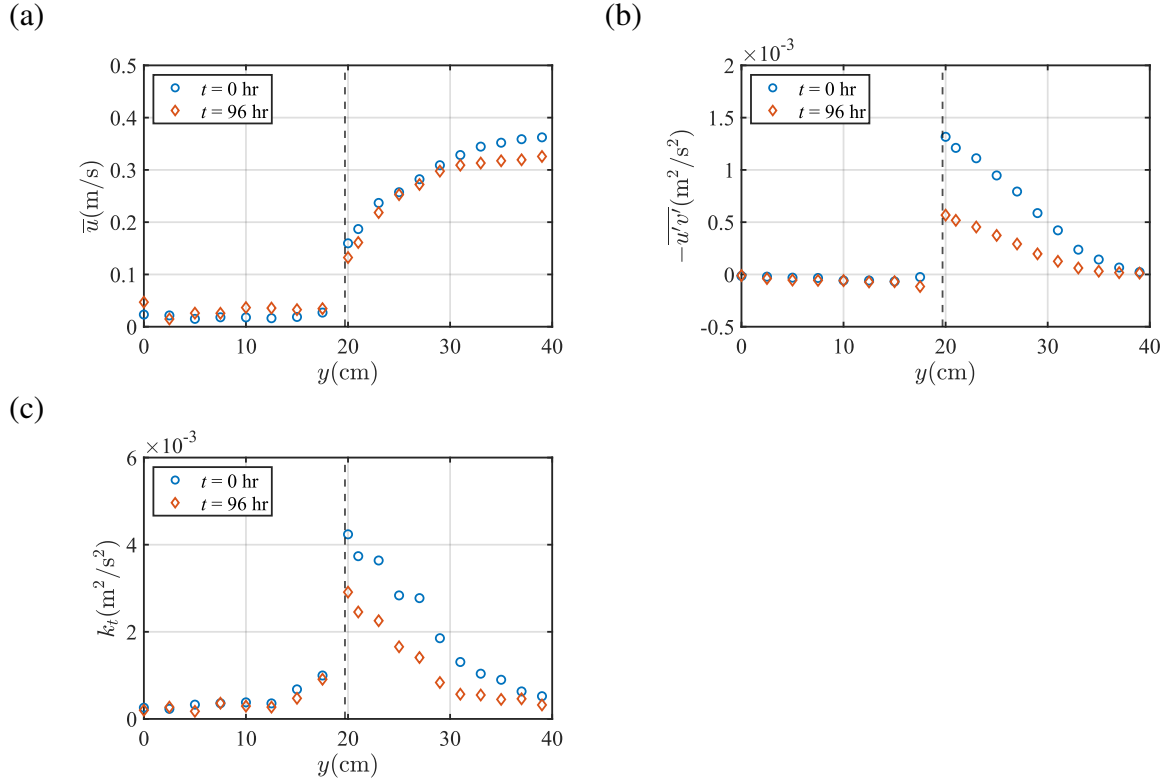


Figure 7.9: Comparison of flow statistics with initially flat bed ( $t = 0$ , blue circles) and with fully-developed bedforms ( $t = 96$  hr, orange symbols). (a) time-averaged streamwise velocity ( $\bar{u}$ ), (b) Reynolds shear stress ( $-\overline{u'v'}$ ), (c) turbulent kinetic energy ( $k_t$ ). Profiles measured at  $x = 249$  cm in the fully-developed region of the patch ( $x > L_i$ ) for high flow blockage canopy ( $C_{Dab} = 3.88$ ). The vertical dashed line indicates the lateral interface of the array,  $y = b$ .

patch and adjacent open channel did not change significantly between the flat bed and deformed bed (compare blue and orange symbols, respectively, in Figure 7.9a). However, the change in flow depth and introduction of bedforms diminished the coherence of the shear-layer vortices along the flow-parallel edge, which was indicated in a diminished Reynolds stress (Figure 7.9b) and turbulence (Figure 7.9c). Because the shear across the flow-parallel patch edges was not significantly reduced (Figure 7.9a), the diminished coherence in the shear-layer vortices was likely due to the introduction of bedforms, associated with a 15% variation in water depth in the open channel region.

The change in bed morphology in the wake led to a change in the von Karman vortex street, which was revealed through dye visualization. With the initially flat bed, a strong von Karman vortex street was observed in the wake, spanning the entire channel width (Figure 7.10a). However, as the bedforms evolved in the wake, the von Karman vortex street became narrower and less coherent over time (Figure 7.10b, c, d). In particular, note the change directly downstream of the patch. At  $t = 0$ , the von Karman vortex street formed close to the patch and carried tracer

upstream to the trailing edge of the patch. At this time, a recirculation zone ( $\bar{u} < 0$ ) was present at the centerline, directly behind the patch (Figure 7.11a,  $t = 0$ ). However, at later times ( $t > 24$  hr), the vortex street formed at a distance from the patch, and no tracer was carried into the region directly behind the patch (Figure 7.10d). In addition, no recirculation was detected in the wake (Figure 7.11a). Further, fine particle deposition occurred in this region, which was visualized due to the dark brown color of the depositing material. Specifically, between  $t = 24$  and 96 hr, a triangular region directly behind the patch became increasingly darker in color (see Figure 7.10c, b, and d). The progressive decline in von Karman vortex strength and coherence was manifest in reduced  $v_{rms}$  (Figure 7.11b), reduced turbulent kinetic energy (Figure 7.11c), and a reduced PSD peak magnitude (compare Figure 7.10e, Figure 7.10f). Note that, even as the strength of the vortex street declined, the dominant frequency remained the same,  $St_b = 2f_{VK}b/U_2 = 0.2$ , which was consistent with similar observations behind circular porous arrays (Zong & Nepf 2012).

## 7.4 Discussion

### 7.4.1 The decay of wake vortex with bed form evolution

The creation of bedforms in the wake increased the bed friction coefficient ( $C_f$ ) and diminished the local flow depth, both of which influenced the wake vortex stability. Consider the wake stability parameter  $S = C_f W/h$ , defined by Chen & Jirka (1995), which can indicate when bed friction suppresses the generation of a von Karman vortex street. For the high flow blockage patch, the wake bedforms grew to a height of  $\Delta = 6$  cm, and length of  $\Lambda = 41$  cm, reducing the water depth from  $h = 20$  to 14 cm. Based on Eq. 3.40, this enhanced the bed friction coefficient from 0.005 to 0.023. As a result, the wake instability parameter,  $S$  changed from 0.01 to 0.07, approaching the critical value  $S_c = 0.09$  at which wake vortices were suppressed behind porous plates ( $\Phi = 0.5$ , Chen & Jirka (1995)). Previous studies have also observed that the wake vortex behind a circular patch (Chang et al. 2017) and a solid cylinder (Kirkil et al. 2008) was weakened as wake bedforms developed. These studies attributed the vortex decay to upwelling mean flow generated by a bedform on the wake centerline. The upwelling flow impeded the interactions of the stream-parallel shear layers, which is the precursor to wake vortex formation, resulting in the two separated shear layers persisting in the wake (Kirkil et al. 2009). Furthermore, Chang et al. (2017) observed that the upwelling motion was weaker after a porous patch relative to the one observed for solid cylinders. In the present experiment, the bed forms were not located on the centerline, and, although the vertical velocity was measured at various locations, no upwelling flow was detected. Thus, the decay of wake vortex in the present work was likely not influenced by the upwelling flow.

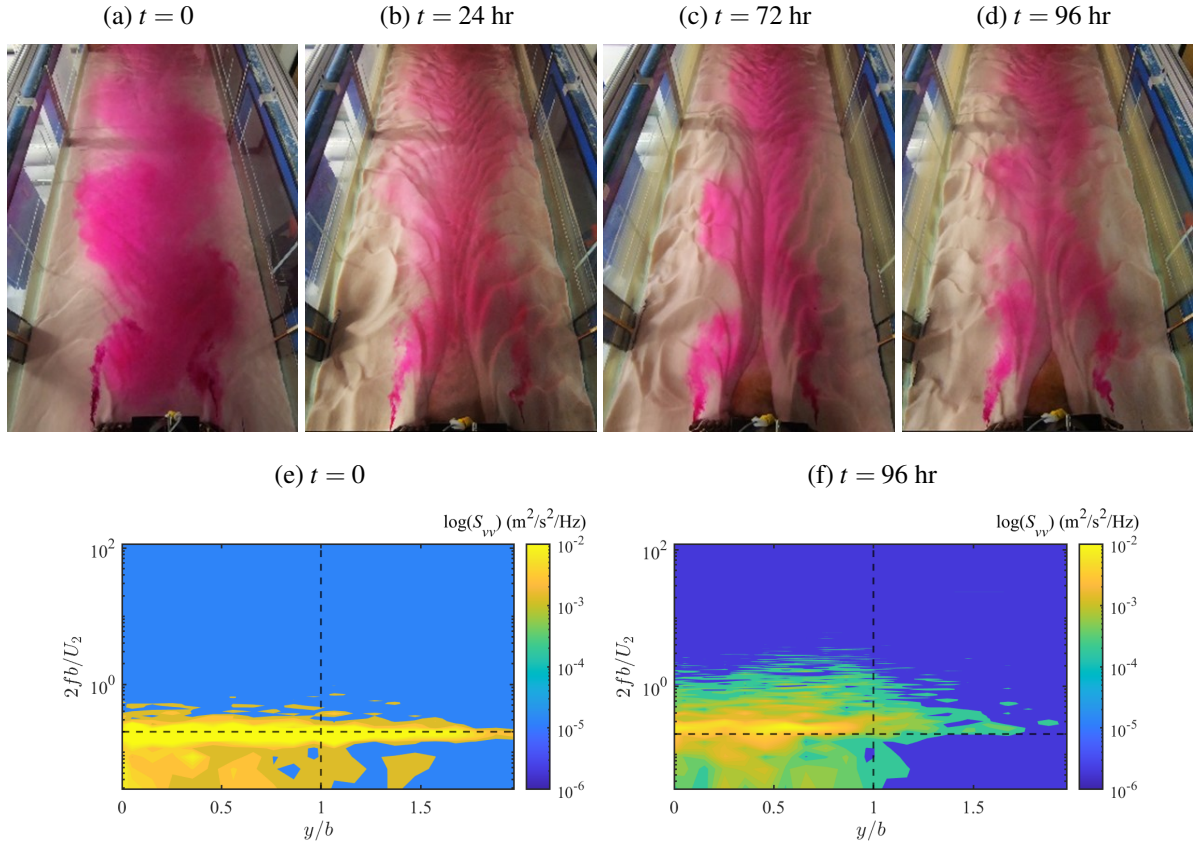


Figure 7.10: (a, b, c, d) As bedforms in the wake grew, the vortex street in the wake was weakened, as illustrated by dye visualization. (e, f) PSD in the wake over flat bed ( $t = 0$ ) and over deformed bed ( $t = 96$  hr), measured at  $x = 318$  cm, which was 50 cm downstream of the trailing edge of the patch and close to the peak of the deposition (Figure 7.3a). The horizontal dashed line indicates the dimensionless frequency of a von Karman vortex  $2f_{VK}b/U_2 = 0.2$ . The vertical dashed line indicates the lateral interface of the array.

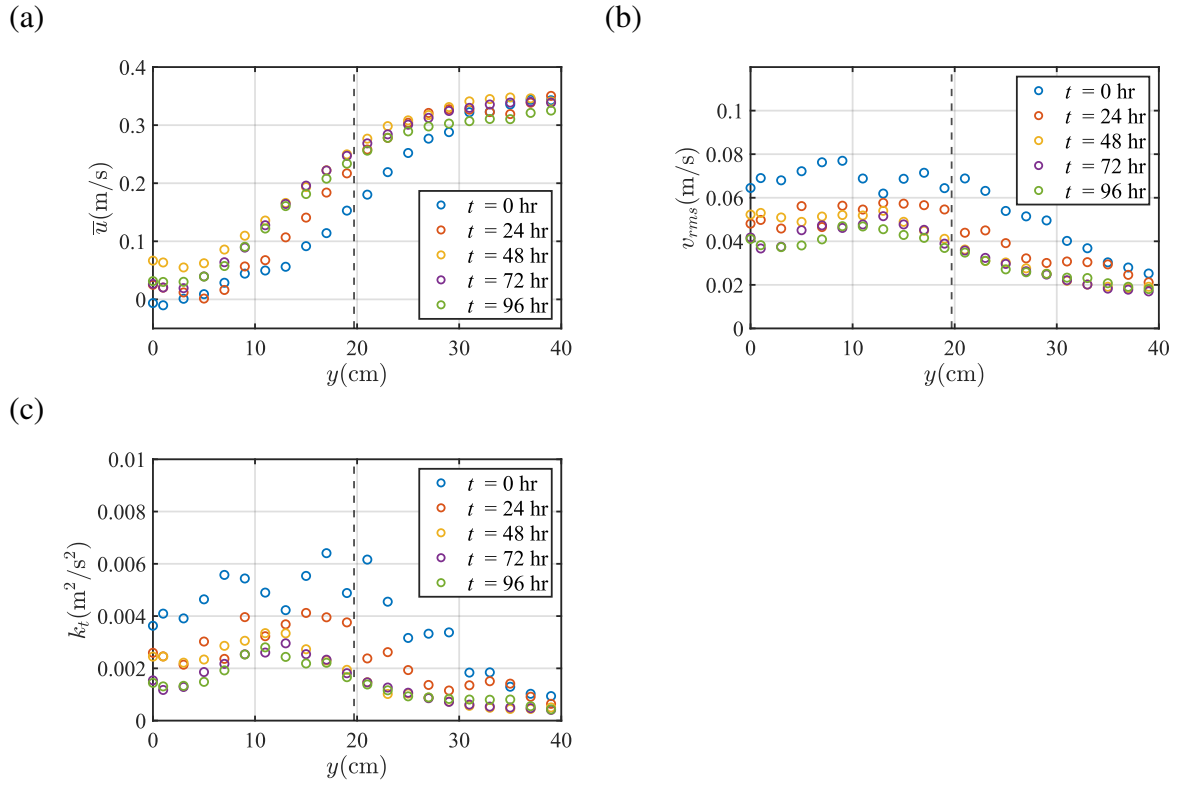


Figure 7.11: The lateral distribution of (a) time-averaged streamwise velocity ( $\bar{u}$ ), (b) fluctuating spanwise velocity ( $v_{rms}$ ), (c) turbulent kinetic energy ( $k_t$ ), at  $x = 318$  cm, i.e., 50 cm after the trailing edge of the patch. The dashed lines indicate half width of the patch,  $y = b$ .

## 7.4.2 Vortex frequency alignment

In the present experiment, and in the similar experiments reported in Chapter 4, the frequency of the KH vortices ( $f_{KH}$ ) at the patch side edges and the frequency of the von Karman vortices ( $f_{VK}$ ) in the patch wakes were the same to within  $\pm 20\%$  (Figure 7.12). In Chapter 4, which used a smaller cylinder diameter ( $d = 3.2$  mm), the synchronization was attributed to the interaction between the KH vortices formed on the two flow-parallel edges and the von Karman vortex in the wake. Specifically, the measured  $f_{KH}$  and  $f_{VK}$  were higher and lower than the predicted value (Table 7.2), respectively, but they matched each other,  $f_{KH} = f_{VK}$ . In the present experiment, there was no interaction between the parallel shear-layers and KH vortices across the patch width (Figure 7.7), which was attributed, in part, to the larger stem size, which produced an edge shear layer strong enough to produce shear sheltering that inhibited the penetration of the KH vortices into the patch. Further, the measured  $f_{KH}$  and  $f_{VK}$  matched their theoretical values (Table 7.2). Specifically, Ho & Huerre (1984) showed that KH vortices within a shear layer have frequency,

$$f_{KH} = \frac{0.032(U_1 + U_2)}{2\theta} \quad (7.1)$$

which has been demonstrated to predict KH vortex frequency in vegetated channels with emergent cylinders (White & Nepf 2008) and for submerged canopies of rigid and flexible plant models (Ghisalberti & Nepf 2002). In addition, based on a large literature for cylinder wakes, the Stouhal number  $St = fD/U \approx 0.2$  for  $200 < Re < 3 \times 10^5$  (Roshko 1961, Schewe 1983). Zong & Nepf (2012) confirmed this for a von Karman vortex street behind a porous patch of cylinders, i.e.,

$$f_{VK} = \frac{0.2U_2}{2b} \quad (7.2)$$

Table 7.2 shows that the observed frequencies for both  $f_{KH}$  and  $f_{VK}$  agreed with the predictions (Eq. 7.1 and 7.2) within uncertainty, suggesting that the similarity between  $f_{KH}$  and  $f_{VK}$  was a coincidence, and not driven by mutual interaction. The absence of vortex synchronization was consistent with the absence of wave response within the patch in the present work.

Finally, we also considered the possible role of stem-scale vortices. For the dense patch, in the fully developed region, the frequency of the stem-scale von Karman vortices was observed in PSD,  $f_d = 0.85$  (Figure 7.13), which was consistent with  $f_d = \frac{StU_1}{d} = 0.8$ , with  $St = 0.2$  and  $U_1 = 0.05$  m/s. Then,  $\frac{f_d}{f_{VK}} = \frac{StU_1/d}{StU_2/2b} = \frac{2bU_1}{U_2d}$ . In this case,  $U_2 = 0.35$  m/s, so  $\frac{f_d}{f_{VK}} = 4.4$ , indicating that  $f_d \gg f_{VK} \approx f_{KH}$ . The difference between the stem-scale frequency and KH frequency is also illustrated in Figure 7.13. The difference suggested that the stem-scale vortex shedding did not influence the patch-scale von Karman vortex street.

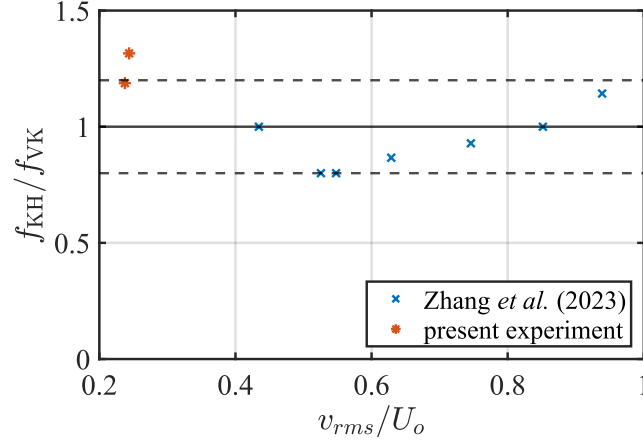


Figure 7.12: Ratio of the von Karman vortex street frequency,  $f_{VK}$ , in the patch wake to the frequency of the KH vortices along the patch edge,  $f_{KH}$ . The solid line indicates  $f_{VK} = f_{KH}$  and the dashed lines indicates  $\pm 20\%$  deviation.

|        | $f_{KH}$ (Hz)                   |                             | $f_{VK}$ (Hz)                   |                            |
|--------|---------------------------------|-----------------------------|---------------------------------|----------------------------|
|        | Predicted $f_{KH}$<br>(Eq. 7.1) | Peak in PSD<br>in the patch | Predicted $f_{VK}$<br>(Eq. 7.2) | Peak in PSD<br>in the wake |
| Dense  | 0.21 (0.02)                     | 0.19 (0.03)                 | 0.17 (0.01)                     | 0.16 (0.03)                |
| Sparse | 0.25 (0.06)                     | 0.25 (0.03)                 | 0.17 (0.01)                     | 0.19 (0.03)                |
| ZA5*   | 0.04 (0.01)                     | 0.12 (0.01)                 | 0.22 (0.01)                     | 0.15 (0.01)                |
| ZB5*   | 0.04 (0.01)                     | 0.16 (0.01)                 | 0.23 (0.01)                     | 0.14 (0.01)                |
| ZC4*   | 0.04 (0.01)                     | 0.13 (0.01)                 | 0.23 (0.01)                     | 0.15 (0.01)                |
| ZC5*   | 0.03 (0.01)                     | 0.14 (0.01)                 | 0.23 (0.01)                     | 0.14 (0.01)                |
| ZD3*   | 0.05 (0.01)                     | 0.14 (0.01)                 | 0.23 (0.01)                     | 0.14 (0.01)                |
| ZD4*   | 0.04 (0.01)                     | 0.13 (0.01)                 | 0.23 (0.01)                     | 0.14 (0.01)                |
| ZD5*   | 0.03 (0.01)                     | 0.12 (0.01)                 | 0.17 (0.01)                     | 0.15 (0.01)                |

Table 7.2: The predicted and measured frequencies for Kelvin–Helmholtz vortices ( $f_{KH}$ ) and von Karman vortices ( $f_{VK}$ ). The asterisk (\*) indicates the data measured in Chapter 4. Numbers in brackets are uncertainties.

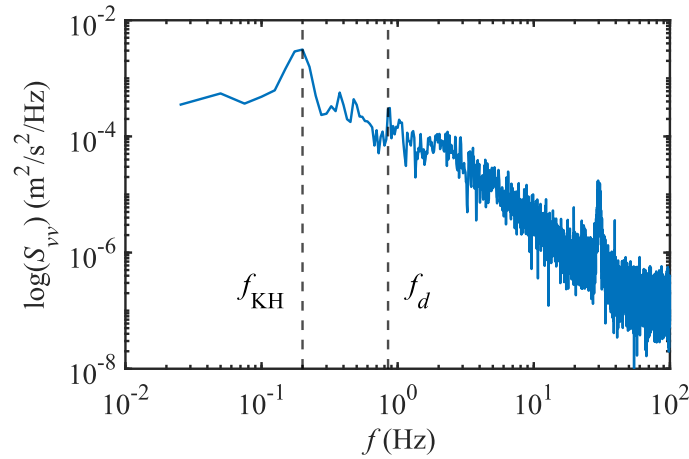


Figure 7.13: Power spectral density of the lateral velocity ( $S_{vv}$ ) at  $(x, y) = (249 \text{ cm}, 20 \text{ cm})$  shows the difference between stem-scale vortex frequency ( $f_d = 0.85 \text{ Hz}$ ) and the Kelvin–Helmholtz vortex frequency ( $f_{KH} = 0.2 \text{ Hz}$ )

## 7.5 Summary

This chapter experimentally investigated the velocity field and bedform development within and around a rectangular array of emergent vegetation. The patch was simulated by rigid dowels arranged in a regular pattern, with two densities representing high-flow and low-flow blockage conditions. An 8-cm layer of uniform sand covered the test section. Velocity measurements and dye visualization were conducted at different running time to evaluate the flow response.

Near the leading edge of the patch, stem-generated turbulence enhanced local turbulent kinetic energy, even as the time-mean velocity decreased. The elevated turbulent kinetic energy produced sediment erosion. A fraction of the eroded sediment was carried downstream within the patch, creating an interior deposition dune. The dune was smaller inside the denser patch, compared to the more sparse patch, because less sediment was eroded and a larger fraction of eroded sediment was transported out of the patch by the strong lateral flow diversion. Specially, the ratio of erosion volume to deposition volume was 24% and 55% for the high and low flow blockage patches, respectively.

In the fully developed region, Kelvin–Helmholtz vortices were initiated within the shear layers developed along the side edges of the patch. However, for both the sparse and dense patches, these vortices were blocked by shear sheltering at the patch edge, and did not penetrate beyond the first row of dowels. Elevated turbulence at the patch edge caused sediment erosion. For the dense patch, the eroded sediment was transported into the patch by the vortex-induced wave response, creating flow-parallel deposition ridges. The process of ridge formation was a redistribution of sediment, but produced no net change in sediment volume within the patch. In contrast, for the sparse patch, sediment scoured at the patch edge was carried away, leading to



sediment loss from the patch.

Sediment eroded from the regions around the patch was deposited in the wake. Because the von Karman vortex street was weak, the lateral transport in the wake was limited to less than the patch half width. As a result, the deposition occurred closer to the wake edge, and not on the wake centerline. The formation of bedforms and the associated increase in bed friction, progressively diminished the von Karman vortex street, due to the enhanced bed friction under a deformed and reduced water depth. Specially, the bed friction coefficient increased from 0.005 to 0.023 and the water depth decreased from 20 cm to 14 cm. As a result, the wake instability parameter,  $S$  changed from 0.01 to 0.07, approaching the critical value  $S_c = 0.09$  at which wake vortices were suppressed behind porous plates. Finally, although the patch generated a significant local redistribution of sediment, it did not provoke channel-scale sediment transport. From the perspective of natural sustainability, a denser patch is recommended to improve sediment retention within the patch.

Further investigation is required to examine the influences of non-uniform sediments, which more closely resemble natural riverbeds. In such scenarios, finer particles are more easily mobilized and transported, while coarser particles tend to remain on the bed surface, forming clusters that contribute to armoring effects. This armoring might alter the flow dynamics and ultimately result in a distinct equilibrium sediment pattern compared to uniform sediment scenarios.

# Chapter 8

## Conclusions, limitations, and future works

### 8.1 Conclusions

This thesis examines flow dynamics and turbulence within and around various configurations of vegetation patches, with particular emphasis on the initiation and interaction of patch-scale shear layers and coherent structures, as well as their interaction with morphological change. The key findings and conclusions can be summarized below.

1. For an in-stream emergent vegetation patch (Chapter 4, 5), patch elongation influences the wake structure by adjusting the bleed flow velocity deficit as well as triggering the Kelvin-Helmholtz vortices along the lateral edges of the patch. Wake von Karman vortex street, unable to be triggered under a low patch density, however, can be generated by patch elongation. Here, patch density indicates the local hydraulic resistance, of which influence can be immediately felt by the local velocity adjustment, shown as the velocity gradient. A larger patch density leads to a faster velocity drop. However, patch dimensions determine the spatial extent of this resistance. A larger patch width delays the flow diversion laterally, leading to an adverse effect on the interior velocity adjustment, while the patch length controls the distance of the velocity drop and triggers the generation of Kelvin-Helmholtz instability along the patch lateral edges. Consequently, larger patch length and vegetation density may lead to higher velocity reduction but patch width presents the opposite impact. The combined effect of vegetation density and patch aspect ratio is representative of cumulative hydraulic resistance. It affects the wake structure by changing the bleed flow velocity and initiating Kelvin-Helmholtz instability at the patch trailing edge. Moreover, the two parallel Kelvin-Helmholtz vortex streets formed along the lateral edges of the patch under sufficiently high aspect ratios tend to interact with each other, leading to velocity recovery owing to transverse momentum input, especially for a smaller width. In contrast to the scenarios of high vegetation density producing

wake flow instability due to inducing large transverse velocity difference, the patch elongation through triggering Kelvin-Helmholtz vortex streets may impose an extra impact on the patch wake vortex street structures. Specially, the initiation of the patch-edge Kelvin-Helmholtz vortex may accelerate the steady wake velocity, shorten the steady wake length and decay the energy of the wake vortex (Chapter 5).

2. In a symmetrical vegetation-channel-vegetation system (Chapter 6), shear layers initiated at the lateral interfaces of the array simultaneously grow in the open region. When the outer shear layer was fully developed before reaching the channel centerline, the production of shear layer-scale turbulent kinetic energy is balanced by the dissipation by bed friction, resulting in a fully-developed outer penetration length. As the array extended laterally, flow confinement appears when the outer shear layers penetrate to the channel centerline. The thickness of each outer penetration was then restricted to the half width of the open region, leading to flow confinement. In general, the flow confinement presents when the full penetration thickness of the outer shear layer is larger than the half width of the open region. However, if the water depth or friction coefficient varies, the threshold value for flow confinement might change because the full penetration thickness of the outer layer is altered. Furthermore, within the shear layer, coherent structures were triggered through Kelvin-Helmholtz instability, with a normalized frequency fairly agrees with the normalized natural frequency of mixing layers. Although the shear-layer vortices can self-organize even under confined conditions, an increase in blockage ratio led to an enhanced vortex frequency, reduced momentum thickness, and increased convection velocity. In confined condition, although the shear layer was confined to one half of the open region and the time-averaged shear stress was zero at the centerline, the shear-layer vortices interact across the open region, observing significant but equal turbulent events. Furthermore, a wavy interface was visualized by dyes released at two side edges, revealing a wave motion with a phase shift of  $\pi$  radians between the parallel vortex streets. The alternating low-pressure vortex cores between the parallel vortex streets amplify the pressure gradient, intensifying coherent structures and facilitating momentum exchange across the channel centerline. While the turbulent intensity improves, the decrease in resident time for the turbulent flow events may lead to shorter transport distances. Consequently, the shear layer developed on one interface acts as an extra resistance to shear turbulence on the opposite interface.
3. To correlate the morphological change with flow structure within and around vegetation patch, a mobile-bed experiment was conducted (Chapter 7). Near the leading edge of the patch, stem-generated turbulence enhanced local turbulent kinetic energy, even as the time-mean velocity decreased. The elevated turbulent kinetic energy produced sediment

erosion. A fraction of the eroded sediment was carried downstream into the patch, creating an interior deposition dune. The dune was smaller inside the denser patch, compared to the more sparse patch, because less sediment was eroded and a larger fraction of eroded sediment was transported out of the patch by the strong lateral flow diversion. In the fully developed region, Kelvin–Helmholtz vortices were initiated within the shear layers developed along the side edges of the patch. However, for both the sparse and dense patches, these vortices were blocked by shear sheltering at the patch edge, and did not penetrate beyond the first row of dowels. Elevated turbulence at the patch edge caused sediment erosion. For the dense patch, the eroded sediment was transported into the patch by the vortex-induced wave response, creating flow-parallel deposition ridges. The process of ridge formation was only a redistribution of sediment, producing no net change in sediment volume within the patch. In contrast, for the sparse patch, sediment scoured at the patch edge was carried away, leading to sediment loss from the patch. Sediment eroded from the regions around the patch was deposited in the wake. Because the von Karman vortex street was weak, the lateral transport in the wake was limited to less than the patch half width. As a result, the deposition occurred closer to the wake edge, and not on the wake centerline. The formation of bedforms and the associated increase in bed friction, progressively diminished, the von Karman vortex street, due to the enhanced bed friction associated with the deformed bed and reduced water depth. Finally, although the patch generated a significant local redistribution of sediment, it did not provoke channel-scale sediment transport. From the perspective of natural sustainability, a denser patch is recommended to improve sediment retention within the patch.

In summary, these findings provide fundamental insights into the mechanics of the interactions among aquatic plants, flow dynamics, and sediment transport, focusing on flow structure formation and interaction, and their resulting bedform development. Such theoretical understanding contribute to developing more reliable approaches to the restoration and management of aquatic ecosystems, ultimately enhancing ecosystem resilience, promoting biodiversity, and ensuring the long-term sustainability of aquatic environments. Last but not least, these findings also contribute to the fundamental understanding of fluid mechanics, particularly in relation to the processes of vortex formation and interaction. These simplified scenarios of vegetation–flow interactions also provides some implications on flow-structure interaction, shedding light on how porous structure influence turbulence, momentum exchange, and overall flow behavior.

## **8.2 Limitations and future work**

Although this thesis provides new insights into flow dynamics and turbulence within and around various configurations of vegetation patches, with particular emphasis on the initiation and in-

teraction of patch-scale shear layers and coherent structures, as well as their interaction with morphological change, there are certain limitations in this research that may constrain its applicability to natural systems:

1. In this thesis, complex natural aquatic plants were simplified and represented as emergent, rigid, circular rods arranged in an aligned pattern. However, in natural aquatic ecosystems, plant configurations are much more complicated, and hydraulic resistance is expected to vary with different arrangements. Real plants have their distinct features that differ across species. For example, plant characteristics can change over time and space, resulting in random configurations, irregular patch shapes, and a broader range of stem sizes and densities. To enhance the applicability of our conclusions to a wider range of scenarios, further investigation into the characteristics of plant arrays is necessary, as factors such as stem size, stem alignment, flexibility, degree of submergence, plant morphology and surface area (skin friction) can all significantly flow velocity and turbulent structure.
2. In this thesis, the incoming flow was designed to be unidirectional, steady, and uniform. However, hydraulic conditions in natural aquatic ecosystems are much more complex, often varying significantly over time and space. In coastal regions, for example, wave action plays a crucial role and should be taken into account. To enhance the applicability of our conclusions to a broader range of natural scenarios, future studies should consider a wider range of flow depths and velocities, as well as unsteady and spatially variable flow conditions, including the presence of waves and multidirectional flows.
3. This thesis considered only a single sediment size. However, bed morphology is strongly influenced by sediment characteristics such as size, density, and cohesion. For instance, smaller and lighter particles are more easily mobilized than larger, heavier ones, so that coarser particles tend to remain on the bed surface, forming clusters that contribute to armoring effects. This armoring effect might in turn alter the flow dynamics and ultimately result in a distinct equilibrium sediment pattern compared to uniform sediment scenarios. Moreover, cohesive sediments exhibit different behaviors compared to non-cohesive sediments. In natural aquatic ecosystems, sediments are typically cohesive and non-uniformly distributed. Consequently, further research into sediment characteristics is essential, as these properties and the resulting bedform significantly affect the bed friction, which will highly affect the sediment motion, flow structure and plant growth.
4. The experiments carried out in this thesis were on the flume scale and short-term, which, while valuable for isolating specific mechanisms, may not fully capture the complexity and variability present in natural environments. To gain a more comprehensive under-

standing of the influence of vegetation on flow and sediment transport over time, long-term and large-scale field investigations should be considered. Such studies would allow for the observation of seasonal and interannual changes, the effects of extreme events, and the cumulative impacts of vegetation on hydrodynamics and sediment dynamics. In addition, field investigations can help validate laboratory findings and improve the accuracy of predictive models, ultimately supporting more effective management and restoration of aquatic ecosystems.

5. This thesis only considered the two-dimensional characteristics of the flow structure, at the middle of the water depth or the water surface. While the flow is primarily horizontal, vertical variations in flow structure can be substantial, particularly in the near-bed region. These near-bed conditions are crucial for accurately predicting sediment transport, as sediment movement is highly sensitive to local shear stresses and turbulence close to the substrate. Therefore, it is essential to undertake high-resolution, three-dimensional investigations that can capture the detailed structure and dynamic response of vegetation to flow. Such studies would provide a more comprehensive understanding of flow-vegetation-sediment interactions and significantly enhance the accuracy of predictive models.

Furthermore, the interactions among vegetation, flow, and sediment are not solely governed by physical processes, they also covers other disciplines, such as biology, fluvial geomorphology, landscape ecology, and geochemistry. For example, biological processes such as plant growth, reproduction, and decay can influence sediment stability and nutrient cycling, while geomorphological dynamics shape habitat structure and connectivity. Landscape ecology provides insights into spatial patterns and ecosystem functions, and geochemical processes affect water quality and sediment composition. By fostering interdisciplinary collaboration, the field of eco-hydraulics can develop more reliable approaches to the restoration and management of aquatic ecosystems, ultimately promoting their resilience, biodiversity, and long-term sustainability.

# References

- Aberle, J. & Järvelä, J. (2013), ‘Flow resistance of emergent rigid and flexible floodplain vegetation’, *Journal of Hydraulic Research* **51**(1), 33–45.
- Ackerman, J. D. & Okubo, A. (1993), ‘Reduced mixing in a marine macrophyte canopy’, *Functional Ecology* **7**(3), 305–309.
- Akao, T., Watanabe, T. & Nagata, K. (2022), ‘Vertical confinement effects on a fully developed turbulent shear layer’, *Physics of Fluids* **34**(5), 055129.
- Aksel, M., Yagci, O., Kirca, V. O., Erdogan, E. & Heidari, N. (2021), ‘A comparative analysis of coherent structures around a pile over rigid-bed and scoured-bottom’, *Ocean Engineering* **226**, 108759.
- Albayrak, I., Nikora, V., Miler, O. & O’Hare, M. (2011), ‘Flow-plant interactions at a leaf scale: effects of leaf shape, serration, roughness and flexural rigidity’, *Aquatic Sciences* **74**(2), 267–286.
- Albayrak, I., Nikora, V., Miler, O. & O’Hare, M. T. (2013), ‘Flow-plant interactions at leaf, stem and shoot scales: drag, turbulence, and biomechanics’, *Aquatic Sciences* **76**(2), 269–294.
- Ali, S. Z. & Dey, S. (2017), ‘Origin of the scaling laws of sediment transport’, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **473**(2197), 20160785.
- Anderson, B., Rutherford, I. & Western, A. (2006), ‘An analysis of the influence of riparian vegetation on the propagation of flood waves’, *Environmental Modelling & Software* **21**(9), 1290–1296. Integrative Modelling of Climatic, Terrestrial and Fluvial Systems.
- Anderson, W., Barros, J. M., Christensen, K. T. & Awasthi, A. (2015), ‘Numerical and experimental study of mechanisms responsible for turbulent secondary flows in boundary layer flows over spanwise heterogeneous roughness’, *Journal of Fluid Mechanics* **768**, 316–347.

- Anjum, N., Pasha, G. A., Ashraf, J., Ghani, U., Abbas, F. M. & Rahman, M. A. (2025), 'How emergent vegetation patch shapes affect flow structure in open channel environments', *Eco-hydrology* **18**(2), e2740.
- Arsénio, P., Rodríguez-González, P. M., Bernez, I., S. Dias, F., Bugalho, M. N. & Dufour, S. (2020), 'Riparian vegetation restoration: Does social perception reflect ecological value?', *River Research and Applications* **36**(6), 907–920.
- Artini, G., Francalanci, S., Solari, L. & Aberle, J. (2024), 'Effects of leafy flexible vegetation on bed-load transport and dune geometry', *Water Resources Research* **60**(10), e2023WR036588.
- Artini, G., Francalanci, S., Solari, L. & Aberle, J. (2025a), 'Effects of leafy flexible vegetation and bedforms on turbulent flow and sediment transport', *Journal of Geophysical Research: Earth Surface* **130**(3), e2024JF007920.
- Artini, G., Francalanci, S., Solari, L. & Aberle, J. (2025b), 'Flow resistance decomposition in the presence of leafy flexible vegetation and sand dunes', *Water Resources Research* **61**(10), e2025WR039942.
- Baas, J. H., Davies, A. G. & Malarkey, J. (2013), 'Bedform development in mixed sand–mud: The contrasting role of cohesive forces in flow and bed', *Geomorphology* **182**, 19–32.
- Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C. & Silliman, B. R. (2011), 'The value of estuarine and coastal ecosystem services', *Ecological Monographs* **81**(2), 169–193.
- Beaumont, N., Jones, L., Garbutt, A., Hansom, J. & Toberman, M. (2014), 'The value of carbon sequestration and storage in coastal habitats', *Estuarine, Coastal and Shelf Science* **137**, 32–40.
- Beechie, T. J., Liermann, M., Pollock, M. M., Baker, S. & Davies, J. (2006), 'Channel pattern and river-floodplain dynamics in forested mountain river systems', *Geomorphology* **78**(1), 124–141.
- Belcher, S. E., Harman, I. N. & Finnigan, J. J. (2012), 'The wind in the willows: Flows in forest canopies in complex terrain', *Annual Review of Fluid Mechanics* **44**(Volume 44, 2012), 479–504.
- Belcher, S. E., Jerram, N. & Hunt, J. C. R. (2003), 'Adjustment of a turbulent boundary layer to a canopy of roughness elements', *Journal of Fluid Mechanics* **488**, 369–398.



- Belliard, J.-P., Toffolon, M., Carniello, L. & D'Alpaos, A. (2015), 'An ecogeomorphic model of tidal channel initiation and elaboration in progressive marsh accretional contexts', *Journal of Geophysical Research: Earth Surface* **120**(6), 1040–1064.
- Ben Meftah, M. & Mossa, M. (2016), 'Partially obstructed channel: Contraction ratio effect on the flow hydrodynamic structure and prediction of the transversal mean velocity profile', *Journal of Hydrology* **542**, 87–100.
- Bennett, S. J., Wu, W., Alonso, C. V. & Wang, S. S. Y. (2008), 'Modeling fluvial response to in-stream woody vegetation: implications for stream corridor restoration', *Earth Surface Processes and Landforms* **33**(6), 890–909.
- Best, J. (2005), *Kinematics, Topology and Significance of Dune-Related Macroturbulence: Some Observations from the Laboratory and Field*, John Wiley and Sons, Ltd, pp. 41–60.
- Biggs, B. J. F. (1996), 'Hydraulic habitat of plants in streams', *Regulated Rivers: Research & Management* **12**(2-3), 131–144.
- Biggs, H. J., Nikora, V. I., Gibbins, C. N., Cameron, S. M., Papadopoulos, K., Stewart, M., Fraser, S., Vettori, D., Savio, M., O'Hare, M. T., Kucher, M. & Hicks, D. M. (2019), 'Flow interactions with an aquatic macrophyte: a field study using stereoscopic particle image velocimetry', *Journal of Ecohydraulics* **4**(2), 113–130.
- Biggs, H. J., Nikora, V. I., Gibbins, C. N., Fraser, S., Green, D. R., Papadopoulos, K. & Hicks, D. M. (2018), 'Coupling unmanned aerial vehicle (uav) and hydraulic surveys to study the geometry and spatial distribution of aquatic macrophytes', *Journal of Ecohydraulics* **3**(1), 45–58.
- Black, K. S., Tolhurst, T. J., Paterson, D. M. & Hagerthey, S. E. (2002), 'Working with natural cohesive sediments', *Journal of Hydraulic Engineering* **128**(1), 2–8.
- Botrel, M. & Maranger, R. (2023), 'Global historical trends and drivers of submerged aquatic vegetation quantities in lakes', *Global Change Biology* **29**(9), 2493–2509.
- Bouma, T., van Duren, L., Temmerman, S., Claverie, T., Blanco-Garcia, A., Ysebaert, T. & Herman, P. (2007), 'Spatial flow and sedimentation patterns within patches of epibenthic structures: Combining field, flume and modelling experiments', *Continental Shelf Research* **27**(8), 1020–1045.
- Bouris, D. & Bergeles, G. (1999), '2d les of vortex shedding from a square cylinder', *Journal of Wind Engineering and Industrial Aerodynamics* **80**(1), 31–46.

- Box, W., Västilä, K. & Järvelä, J. (2019), 'The interplay between flow field, suspended sediment concentration, and net deposition in a channel with flexible bank vegetation', *Water* **11**(11).
- Branß, T. & Aberle, J. (2022), 'Combined effect of a mobile bed and floodplain edge vegetation on compound channel conveyance', *Journal of Hydraulic Research* **60**(5), 826–834.
- Branß, T., Núñez-González, F. & Aberle, J. (2022), 'Fluvial levees in compound channels: a review on formation processes and the impact of bedforms and vegetation', *Environmental Fluid Mechanics* **22**(2), 559–585.
- Brown, G. L. & Roshko, A. (1974), 'On density effects and large structure in turbulent mixing layers', *Journal of Fluid Mechanics* **64**(4), 775–816.
- Calvani, G., Francalanci, S. & Solari, L. (2019), 'A physical model for the uprooting of flexible vegetation on river bars', *Journal of Geophysical Research: Earth Surface* **124**(4), 1018–1034.
- Caroppi, G., Gualtieri, P., Fontana, N. & Giugni, M. (2020), 'Effects of vegetation density on shear layer in partly vegetated channels', *Journal of Hydro-environment Research* **30**, 82–90.
- Caroppi, G., Västilä, K., Gualtieri, P., Järvelä, J., Giugni, M. & Rowiński, P. M. (2021), 'Comparison of flexible and rigid vegetation induced shear layers in partly vegetated channels', *Water Resources Research* **57**(3), e2020WR028243.
- Caroppi, G., Västilä, K., Järvelä, J., Rowiński, P. M. & Giugni, M. (2019), 'Turbulence at water-vegetation interface in open channel flow: Experiments with natural-like plants', *Advances in Water Resources* **127**, 180–191.
- Castro, I. P. (1971), 'Wake characteristics of two-dimensional perforated plates normal to an air-stream', *Journal of Fluid Mechanics* **46**(3), 599–609.
- Caulfield, C. P., Peltier, W. R., Yoshida, S. & Ohtani, M. (1995), 'An experimental investigation of the instability of a shear flow with multilayered density stratification', *Physics of Fluids* **7**(12), 3028–3041.
- Celik, A. O., Diplas, P., Dancey, C. L. & Valyrakis, M. (2010), 'Impulse and particle dislodgement under turbulent flow conditions', *Physics of Fluids* **22**(4), 046601.
- Chakraborty, P. & Sarkar, A. (2016), 'Flow characteristics through submerged rigid vegetation over a sinusoidal perturbed bed', *International Journal of River Basin Management* **14**(3), 255–266.

- Chang, K. & Constantinescu, G. (2013), 'Coherent structures in flow over two-dimensional dunes', *Water Resources Research* **49**(5), 2446–2460.
- Chang, K. & Constantinescu, G. (2015), 'Numerical investigation of flow and turbulence structure through and around a circular array of rigid cylinders', *Journal of Fluid Mechanics* **776**, 161–199.
- Chang, W.-Y., Constantinescu, G. & Tsai, W. F. (2017), 'On the flow and coherent structures generated by a circular array of rigid emerged cylinders placed in an open channel with flat and deformed bed', *Journal of Fluid Mechanics* **831**, 1–40.
- Chang, Y. S. & Scotti, A. (2003), 'Entrainment and suspension of sediments into a turbulent flow over ripples', *Journal of Turbulence* **4**(1), 019.
- Chembolu, V., Kakati, R. & Dutta, S. (2019), 'A laboratory study of flow characteristics in natural heterogeneous vegetation patches under submerged conditions', *Advances in Water Resources* **133**, 103418.
- Chen, D. & Jirka, G. H. (1995), 'Experimental study of plane turbulent wakes in a shallow water layer', *Fluid Dynamics Research* **16**(1), 11–41.
- Chen, J.-H., Pritchard, W. G. & Tavener, S. J. (1995), 'Bifurcation for flow past a cylinder between parallel planes', *Journal of Fluid Mechanics* **284**, 23–41.
- Chen, S.-C., Chan, H.-C. & Li, Y.-H. (2012), 'Observations on flow and local scour around submerged flexible vegetation', *Advances in Water Resources* **43**, 28–37.
- Chen, S.-C., Kuo, Y.-M. & Li, Y.-H. (2011), 'Flow characteristics within different configurations of submerged flexible vegetation', *Journal of Hydrology* **398**(1), 124–134.
- Chen, Z., Jiang, C. & Nepf, H. (2013), 'Flow adjustment at the leading edge of a submerged aquatic canopy', *Water Resources Research* **49**(9), 5537–5551.
- Chen, Z., Ortiz, A., Zong, L. & Nepf, H. (2012), 'The wake structure behind a porous obstruction and its implications for deposition near a finite patch of emergent vegetation', *Water Resources Research* **48**(9), W09517.
- Cheng, N., Wei, M. & Lu, Y. (2020), 'Critical flow velocity for incipient sediment motion in open channel flow with rigid emergent vegetation', *Journal of Engineering Mechanics* **146**(11), 04020123.
- Choi, S.-U. & Kang, H. (2006), 'Numerical investigations of mean flow and turbulence structures of partly-vegetated open-channel flows using the reynolds stress model', *Journal of Hydraulic Research* **44**(2), 203–217.

- Choi, S.-U. & Kang, H. (2016), ‘Characteristics of mean flow and turbulence statistics of depth-limited flows with submerged vegetation in a rectangular open-channel’, *Journal of Hydraulic Research* **54**(5), 527–540.
- Chu, V. H., Wu, J. & Khayat, R. E. (1991), ‘Stability of transverse shear flows in shallow open channels’, *Journal of Hydraulic Engineering* **117**(10), 1370–1388.
- Coleman, J. M., Huh, O. K. & Braud, DeWitt, J. (2008), ‘Wetland loss in world deltas’, *Journal of Coastal Research* (24 (10024)), 1–14.
- Colombini, M. & Stocchino, A. (2005), ‘Coupling or decoupling bed and flow dynamics: Fast and slow sediment waves at high froude numbers’, *Physics of Fluids* **17**(3), 036602.
- Colombini, M. & Stocchino, A. (2012), ‘Three-dimensional river bed forms’, *Journal of Fluid Mechanics* **695**, 63–80.
- Conde-Frias, M., Ghisalberti, M., Lowe, R. J., Abdolahpour, M. & Etminan, V. (2023), ‘The near-bed flow structure and bed shear stresses within emergent vegetation’, *Water Resources Research* **59**(4), e2022WR032499.
- Corenblit, D., Tabacchi, E., Steiger, J. & Gurnell, A. M. (2007), ‘Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches’, *Earth-Science Reviews* **84**(1), 56–86.
- Cornacchia, L., Riviere, N., Soundar Jerome, J. J., Doppler, D., Vallier, F. & Puijalon, S. (2022), ‘Flow and wake length downstream of live submerged vegetation patches: How do different species and patch configurations create sheltering in stressful habitats?’, *Water Resources Research* **58**(3), e2021WR030880.
- Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S. & Turner, R. K. (2014), ‘Changes in the global value of ecosystem services’, *Global Environmental Change* **26**, 152–158.
- Coutanceau, M. & Bouard, R. (1977), ‘Experimental determination of the main features of the viscous flow in the wake of a circular cylinder in uniform translation. part 1. steady flow’, *Journal of Fluid Mechanics* **79**(2), 231–256.
- Couvillion, B. R., Beck, H., Schoolmaster, D. & Fischer, M. (2017), Land area change in coastal louisiana (1932 to 2016), Technical report, US Geological Survey.
- Creed, M. J., Draper, S., Nishino, T. & Borthwick, A. G. L. (2017), ‘Flow through a very porous obstacle in a shallow channel’, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **473**(2200), 20160672.

- Dargahi, B. (1990), 'Controlling mechanism of local scouring', *Journal of Hydraulic Engineering* **116**(10), 1197–1214.
- de Lima, P. H. S., Janzen, J. G. & Nepf, H. M. (2015), 'Flow patterns around two neighboring patches of emergent vegetation and possible implications for deposition and vegetation growth', *Environmental Fluid Mechanics* **15**(4), 881–898.
- Debnath, K., Manik, M. & Mazumder, B. (2012), 'Turbulence statistics of flow over scoured cohesive sediment bed around circular cylinder', *Advances in Water Resources* **41**, 18–28.
- Dehsorkhi, E. N., Afzalimehr, H., Gallichand, J. & Rousseau, A. N. (2013), 'Turbulence measurements above sharp-crested gravel bedforms', *International Journal of Hydraulic Engineering* **2**(5), 101–114.
- Dehsorkhi, E. N., Afzalimehr, H. & Singh, V. P. (2011), 'Effect of bed forms and vegetated banks on velocity distributions and turbulent flow structure', *Journal of Hydrologic Engineering* **16**(6), 495–507.
- Deitrick, A. R., Hovendon, E. H., Ralston, D. K. & Nepf, H. (2023), 'The influence of vegetation-generated turbulence on deposition in emergent canopies', *Frontiers in Marine Science* **Volume 10 - 2023**.
- Deitrick, A. R., Ralston, D. K., Esposito, C. R., Baustian, M. M., Burgos, M. B., Courtois, A. J. & Nepf, H. (2024), 'Vegetation-generated turbulence does not impact the erosion of natural cohesive sediment', *Geophysical Research Letters* **51**(14), e2024GL109730.
- Dosskey, M. G., Vidon, P., Gurwick, N. P., Allan, C. J., Duval, T. P. & Lowrance, R. (2010), 'The role of riparian vegetation in protecting and improving chemical water quality in streams', *JAWRA Journal of the American Water Resources Association* **46**(2), 261–277.
- Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P. & Côté, I. M. (2021), 'Long-term declines and recovery of meadow area across the world's seagrass bioregions', *Global Change Biology* **27**(17), 4096–4109.
- Dupuis, V., Proust, S., Berni, C. & Paquier, A. (2017), 'Mixing layer development in compound channel flows with submerged and emergent rigid vegetation over the floodplains', *Experiments in Fluids* **58**(4), 30.
- Dupuis, V., Schraen, L. & Eiff, O. (2023), 'Shear layers in two-stage compound channels investigated with ls-piv', *Experiments in Fluids* **64**(2), 24.
- Edmaier, K., Crouzy, B. & Perona, P. (2015), 'Experimental characterization of vegetation uprooting by flow', *Journal of Geophysical Research: Biogeosciences* **120**(9), 1812–1824.

- El Ganaoui, O., Schaaff, E., Boyer, P., Amielh, M., Anselmet, F. & Grenz, C. (2004), 'The deposition and erosion of cohesive sediments determined by a multi-class model', *Estuarine, Coastal and Shelf Science* **60**(3), 457–475.
- Elsey-Quirk, T., Lynn, A., Jacobs, M. D., Diaz, R., Cronin, J. T., Wang, L., Huang, H. & Justic, D. (2024), 'Vegetation dieback in the mississippi river delta triggered by acute drought and chronic relative sea-level rise', *Nature Communications* **15**(1), 3518.
- Escauriaza, C. & Sotiropoulos, F. (2011), 'Initial stages of erosion and bed form development in a turbulent flow around a cylindrical pier', *Journal of Geophysical Research: Earth Surface* **116**(F3).
- Etminan, V., Lowe, R. J. & Ghisalberti, M. (2017), 'A new model for predicting the drag exerted by vegetation canopies', *Water Resources Research* **53**(4), 3179–3196.
- Euler, T., Zemke, J., Rodrigues, S. & Herget, J. (2014), 'Influence of inclination and permeability of solitary woody riparian plants on local hydraulic and sedimentary processes', *Hydrological Processes* **28**(3), 1358–1371.
- Fagherazzi, S., Bryan, K. R. & Nardin, W. (2017), 'Buried alive or washed away: The challenging life of mangroves in the mekong delta', *Oceanography* **30**(3), 48–59.
- Fairchild, T. P., Bennett, W. G., Smith, G., Day, B., Skov, M. W., Möller, I., Beaumont, N., Karunarathna, H. & Griffin, J. N. (2021), 'Coastal wetlands mitigate storm flooding and associated costs in estuaries', *Environmental Research Letters* **16**(7), 074034.
- Fedele, J. J. & García, M. H. (2001), *Alluvial Roughness in Streams with Dunes: A Boundary-Layer Approach*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 37–60.
- Finnigan, J. J., SHAW, R. H. & PATTON, E. G. (2009), 'Turbulence structure above a vegetation canopy', *Journal of Fluid Mechanics* **637**, 387–424.
- Follett, E. M. & Nepf, H. M. (2012), 'Sediment patterns near a model patch of reedy emergent vegetation', *Geomorphology* **179**, 141–151.
- Follett, E. & Nepf, H. (2018), 'Particle retention in a submerged meadow and its variation near the leading edge', *Estuaries and Coasts* **41**, 724–733.
- Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., Apostolaki, E. T., Kendrick, G. A., Krause-Jensen, D., McGlathery, K. J. & Serrano, O. (2012), 'Seagrass ecosystems as a globally significant carbon stock', *Nature Geoscience* **5**(7), 505–509.

- Fu, J., He, G., Huang, L., Dey, S. & Fang, H. (2023), 'Swaying motions of submerged flexible vegetation', *Journal of Fluid Mechanics* **971**, A14.
- Ghisalberti, M. & Nepf, H. (2005), 'Mass transport in vegetated shear flows', *Environmental fluid mechanics* **5**, 527–551.
- Ghisalberti, M. & Nepf, H. (2006), 'The structure of the shear layer in flows over rigid and flexible canopies', *Environmental Fluid Mechanics* **6**, 277–301.
- Ghisalberti, M. & Nepf, H. M. (2002), 'Mixing layers and coherent structures in vegetated aquatic flows', *Journal of Geophysical Research: Oceans* **107**(C2), 3–1–3–11.
- Ghisalberti, M. & Nepf, H. M. (2004), 'The limited growth of vegetated shear layers', *Water Resources Research* **40**(7), W07502.
- Ghisalberti, M. & Nepf, H. M. (2009), 'Shallow flows over a permeable medium: the hydrodynamics of submerged aquatic canopies', *Transport in porous media* **78**(2), 309–326.
- Gioia, G. & Bombardelli, F. A. (2001), 'Scaling and similarity in rough channel flows', *Phys. Rev. Lett.* **88**, 014501.
- Goring, D. G. & Nikora, V. I. (2002), 'Despiking acoustic doppler velocimeter data', *Journal of Hydraulic Engineering* **128**(1), 117–126.
- Gran, K. B., Tal, M. & Wartman, E. D. (2015), 'Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system, mount pinatubo, philippines', *Earth Surface Processes and Landforms* **40**(8), 1101–1115.
- Greiner, J. T., McGlathery, K. J., Gunnell, J. & McKee, B. A. (2013), 'Seagrass restoration enhances "blue carbon" sequestration in coastal waters', *PLOS ONE* **8**(8), null.
- Gu, J., Shan, Y., Liu, C. & Liu, X. (2019), 'Feedbacks of flow and bed morphology from a submerged dense vegetation patch without upstream sediment supply', *Environmental Fluid Mechanics* **19**, 475–493.
- Guan, M. & Liang, Q. (2017), 'A two-dimensional hydro-morphological model for river hydraulics and morphology with vegetation', *Environmental Modelling & Software* **88**, 10–21.
- Gui, Z., Shan, Y., Li, C., Sun, S. & Liu, C. (2024), 'Turbulence and sediment deposition in a channel with floating vegetation', *Journal of Hydrology* **641**, 131829.
- Gui, Z., Shan, Y. & Liu, C. (2023), 'Flow velocity evolution through a floating rigid cylinder array under unidirectional flow', *Journal of Hydrology* **617**, 128915.

- Gui, Z., Shan, Y. & Liu, C. (2024), 'Flow velocity adjustment in a channel with a floating vegetation canopy', *Journal of Hydrology* **628**, 130528.
- Gurnell, A. (2014), 'Plants as river system engineers', *Earth Surface Processes and Landforms* **39**(1), 4–25.
- Gurnell, A. M., Bertoldi, W. & Corenblit, D. (2012), 'Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers', *Earth-Science Reviews* **111**(1), 129–141.
- Gurnell, A., Thompson, K., Goodson, J. & Moggridge, H. (2008), 'Propagule deposition along river margins: linking hydrology and ecology', *Journal of Ecology* **96**(3), 553–565.
- Habib, S. & Tanaka, N. (2025), 'Effect of vegetation type and location on the change of alternate sandbars in a straight river channel', *International Journal of Civil Engineering* **23**(9), 1735–1751.
- Han, L., Zeng, Y., Chen, L. & Huai, W. (2016), 'Lateral velocity distribution in open channels with partially flexible submerged vegetation', *Environmental Fluid Mechanics* **16**, 1267–1282.
- He, F., An, H., Ghisalberti, M., Draper, S., Ren, C., Branson, P. & Cheng, L. (2024), 'Obstacle arrangement can control flows through porous obstructions', *Journal of Fluid Mechanics* **992**, A3.
- He, F., Ghisalberti, M., An, H., Draper, S., Branson, P., Ren, C. & Cheng, L. (2024), 'Wake structure of an array of cylinders in shallow flow', *Journal of Fluid Mechanics* **986**, A30.
- He, L., Shan, Y.-q., Liu, C., Cao, H., Liu, X.-n. & Guo, Y. (2024), 'Prediction of bedload transport inside vegetation canopies with natural morphology', *Journal of Hydrodynamics* **36**(3), 556–569.
- He, S., Liu, H. & Shen, L. (2022), 'Simulation-based study of turbulent aquatic canopy flows with flexible stems', *Journal of Fluid Mechanics* **947**, A33.
- Henry, C., Amoros, C. & Bornette, G. (1996), 'Species traits and recolonization processes after flood disturbances in riverine macrophytes', *Vegetatio* **122**, 13–27.
- Ho, C. M. & Huerre, P. (1984), 'Perturbed free shear layers', *Annual Review of Fluid Mechanics* **16**, 365–424.
- Horppila, J. & Nurminen, L. (2001), 'The effect of an emergent macrophyte (typha angustifolia) on sediment resuspension in a shallow north temperate lake', *Freshwater Biology* **46**(11), 1447–1455.



- Hosseini, N., Griffith, M. & Leontini, J. (2020), ‘The flow past large numbers of cylinders in tandem’, *Journal of Fluids and Structures* **98**, 103103.
- Hou, X., Liu, J., Huang, H., Zhang, Y., Liu, C. & Gong, P. (2024), ‘Mapping global lake aquatic vegetation dynamics using 10-m resolution satellite observations’, *Science Bulletin* **69**(19), 3115–3126.
- Hu, Z., Lei, J., Liu, C. & Nepf, H. (2018), ‘Wake structure and sediment deposition behind models of submerged vegetation with and without flexible leaves’, *Advances in Water Resources* **118**, 28–38.
- Huai, W.-X., Zhang, J., Wang, W.-J. & Katul, G. G. (2019), ‘Turbulence structure in open channel flow with partially covered artificial emergent vegetation’, *Journal of Hydrology* **573**, 180–193.
- Huai, W., Xue, W. & Qian, Z. (2015), ‘Large-eddy simulation of turbulent rectangular open-channel flow with an emergent rigid vegetation patch’, *Advances in Water Resources* **80**, 30–42.
- Hunt, J. C. R. & Durbin, P. A. (1999), ‘Perturbed vortical layers and shear sheltering’, *Fluid Dynamics Research* **24**(6), 375.
- Hurther, D. & Thorne, P. D. (2011), ‘Suspension and near-bed load sediment transport processes above a migrating, sand-rippled bed under shoaling waves’, *Journal of Geophysical Research: Oceans* **116**(C7).
- James, C. S., Birkhead, A. L., Jordanova, A. A. & O’Sullivan, J. J. (2004), ‘Flow resistance of emergent vegetation’, *Journal of Hydraulic Research* **42**(4), 390–398.
- Jerolmack, D. & Mohrig, D. (2005), ‘Interactions between bed forms: Topography, turbulence, and transport’, *Journal of Geophysical Research: Earth Surface* **110**(F2).
- Jia, Y.-Y., Yao, Z.-D., Duan, H.-F., Wang, X.-K. & Yan, X.-F. (2022), ‘Numerical assessment of canopy blocking effect on partly-obstructed channel flows: from perturbations to vortices’, *Engineering Applications of Computational Fluid Mechanics* **16**(1), 1761–1780.
- Jourdain, C., Claude, N., Tassi, P., Cordier, F. & Antoine, G. (2020), ‘Morphodynamics of alternate bars in the presence of riparian vegetation’, *Earth Surface Processes and Landforms* **45**(5), 1100–1122.
- Julien, P. Y. (2010), *Erosion and sedimentation*, Cambridge university press.

- Jumain, M., Ibrahim, Z., Ismail, Z., Entalai, K., Makhtar, M. R., Rahman, M. S. A. & Alias, N. (2018), 'Influence of riparian vegetation on flow resistance in mobile bed straight compound channels', *Journal of Physics: Conference Series* **1049**(1), 012027.
- Kabiri, F., Afzalimehr, H. & Sui, J. (2017), 'Flow structure over a wavy bed with vegetation cover', *International Journal of Sediment Research* **32**(2), 186–194.
- Kalarty, T. P., Fourniotis, N. T. & Tzirtzilakis, E. E. (2025), 'Numerical study of turbulent open-channel flow through submerged rigid vegetation', *Water* **17**(14).
- Kalidindi, M. K. & Khosa, R. (2024), 'Evolution of coherent structures in the flow around a circular pier with a developing scour hole: A numerical study', *Physics of Fluids* **36**(2), 025119.
- Kemp, J. L., Harper, D. M. & Crosa, G. A. (2000), 'The habitat-scale ecohydraulics of rivers', *Ecological Engineering* **16**(1), 17–29.
- Kim, H. D., Yu, X. & Kaplan, D. (2024), 'Steady flow over a finite patch of submerged flexible vegetation', *Water Resources Research* **60**(1), e2023WR035222.
- Kim, H. S., Kimura, I. & Park, M. (2018), 'Numerical simulation of flow and suspended sediment deposition within and around a circular patch of vegetation on a rigid bed', *Water Resources Research* **54**(10), 7231–7251.
- Kim, H. S., Kimura, I. & Shimizu, Y. (2015), 'Bed morphological changes around a finite patch of vegetation', *Earth Surface Processes and Landforms* **40**(3), 375–388.
- Kim, H. S., Kimura, I. & Shimizu, Y. (2019), 'Experiment and computation of morphological response to a vegetation patch in open-channel flows with erodible banks', *Water* **11**(11).
- Kim, H. S., Nabi, M., Kimura, I. & Shimizu, Y. (2015), 'Computational modeling of flow and morphodynamics through rigid-emergent vegetation', *Advances in Water Resources* **84**, 64–86.
- King, A. T., Tinoco, R. O. & Cowen, E. A. (2012), 'A  $k-\epsilon$  turbulence model based on the scales of vertical shear and stem wakes valid for emergent and submerged vegetated flows', *Journal of Fluid Mechanics* **701**, 1–39.
- Kirkil, G. & Constantinescu, G. (2010), 'Flow and turbulence structure around an in-stream rectangular cylinder with scour hole', *Water Resources Research* **46**(11).
- Kirkil, G., Constantinescu, G. & Ettema, R. (2009), 'Detached eddy simulation investigation of turbulence at a circular pier with scour hole', *Journal of Hydraulic Engineering* **135**(11), 888–901.

- Kirkil, G., Constantinescu, S. G. & Ettema, R. (2008), 'Coherent structures in the flow field around a circular cylinder with scour hole', *Journal of Hydraulic Engineering* **134**(5), 572–587.
- Kirzhner, F., Zimmels, Y., Malkovskaja, A. & Starosvetsky, J. (2009), 'Removal of microbial biofilm on water hyacinth plants roots by ultrasonic treatment', *Ultrasonics* **49**(2), 153–158.
- Kitsikoudis, V., Yagci, O., Kirca, V. S. O. & Kellecioglu, D. (2016), 'Experimental investigation of channel flow through idealized isolated tree-like vegetation', *Environmental Fluid Mechanics* **16**(6), 1283–1308.
- Klösch, M. & Habersack, H. (2017), 'The hydromorphological evaluation tool (hymet)', *Geomorphology* **291**, 143–158.
- Koken, M. & Constantinescu, G. (2021), 'Flow structure inside and around a rectangular array of rigid emerged cylinders located at the sidewall of an open channel', *Journal of Fluid Mechanics* **910**, A2.
- Koken, M. & Constantinescu, G. (2023), 'Influence of submergence ratio on flow and drag forces generated by a long rectangular array of rigid cylinders at the sidewall of an open channel', *Journal of Fluid Mechanics* **966**, A5.
- Konings, A. G., Katul, G. G. & Thompson, S. E. (2012), 'A phenomenological model for the flow resistance over submerged vegetation', *Water Resources Research* **48**(2).
- Kumar, P., Kumar, A. & Sharma, A. (2025), 'Hydrodynamics and bed morphology in a double-layered partially vegetated mobile bed channel', *Physics of Fluids* **37**(3), 035210.
- Kumar, P. & Sharma, A. (2025a), 'Experimental analysis of vegetation heterogeneity on flow characteristics and bed morphology in partially vegetated channels', *Earth Surface Processes and Landforms* **50**(13), e70174.
- Kumar, P. & Sharma, A. (2025b), 'Impact of emergent vegetation on three-dimensional turbulent flow properties and bed morphology in a partially vegetated channel', *International Journal of Sediment Research* **40**(2), 286–311.
- Kwoll, E., Venditti, J. G., Bradley, R. W. & Winter, C. (2016), 'Flow structure and resistance over subaqueous high- and low-angle dunes', *Journal of Geophysical Research: Earth Surface* **121**(3), 545–564.
- Larsen, L. G. & Harvey, J. W. (2010), 'How vegetation and sediment transport feedbacks drive landscape change in the everglades and wetlands worldwide.', *The American Naturalist* **176**(3), E66–E79.

- Le Bouteiller, C. & Venditti, J. G. (2014), 'Vegetation-driven morphodynamic adjustments of a sand bed', *Geophysical Research Letters* **41**(11), 3876–3883.
- Le Bouteiller, C. & Venditti, J. G. (2015), 'Sediment transport and shear stress partitioning in a vegetated flow', *Water Resources Research* **51**(4), 2901–2922.
- Lee, S. O. & Sturm, T. W. (2009), 'Effect of sediment size scaling on physical modeling of bridge pier scour', *Journal of Hydraulic Engineering* **135**(10), 793–802.
- Lefebvre, A., Paarlberg, A. J. & Winter, C. (2014), 'Flow separation and shear stress over angle-of-repose bed forms: A numerical investigation', *Water Resources Research* **50**(2), 986–1005.
- Lei, J. & Nepf, H. (2021), 'Evolution of flow velocity from the leading edge of 2-d and 3-d submerged canopies', *Journal of Fluid Mechanics* **916**, A36.
- Leonard, L. A. & Luther, M. E. (1995), 'Flow hydrodynamics in tidal marsh canopies', *Limnology and Oceanography* **40**(8), 1474–1484.
- Leonard, L. A. & Reed, D. (2002), 'Hydrodynamics and sediment transport through tidal marsh canopies', *Journal of Coastal Research* (36 (10036)), 459–469.
- Leonard, L., Croft, A., Childers, D., Mitchell-Bruker, S., Solo-Gabriele, H. & Ross, M. (2006), 'Characteristics of surface-water flows in the ridge and slough landscape of everglades national park: implications for particulate transport', *Hydrobiologia* **569**, 5–22.
- Li, D., Liu, M. & Huai, W. (2022), 'Modeling transverse momentum exchange in partially vegetated flow', *Physics of Fluids* **34**(2), 025124.
- Li, F., Shan, Y., Li, M., Guo, Y. & Liu, C. (2024), 'Insights for river restoration: The impacts of vegetation canopy length and canopy discontinuity on riverbed evolution', *Water Resources Research* **60**(7), e2023WR036473.
- Li, J., Claude, N., Tassi, P., Cordier, F., Vargas-Luna, A., Crosato, A. & Rodrigues, S. (2022), 'Effects of vegetation patch patterns on channel morphology: A numerical study', *Journal of Geophysical Research: Earth Surface* **127**(5), e2021JF006529.
- Li, J.-F., Chiu, Y.-Y. & Chen, S.-C. (2025), 'Impact of vegetation roots on erosion protection of sandbars in laboratory experiments', *CATENA* **249**, 108631.
- Li, Q., Zeng, Y.-h. & Bai, Y. (2020), 'Mean flow and turbulence structure of open channel flow with suspended vegetation', *Journal of Hydrodynamics* **32**, 314–325.

- Li, S. & Katul, G. (2019), ‘Cospectral budget model describes incipient sediment motion in turbulent flows’, *Phys. Rev. Fluids* **4**, 093801.
- Li, W., Liu, B. & Hu, P. (2023), ‘Fast modeling of vegetated flow and sediment transport over mobile beds using shallow water equations with anisotropic porosity’, *Water Resources Research* **59**(3), e2021WR031896.
- Li, W., Wang, D., Jiao, J. & Yang, K. (2019), ‘Effects of vegetation patch density on flow velocity characteristics in an open channel’, *Journal of Hydrodynamics* **31**(5), 1052–1059.
- Li, Y.-H., Xie, L. & chow Su, T. (2018), ‘Resistance of open-channel flow under the effect of bending deformation of submerged flexible vegetation’, *Journal of Hydraulic Engineering* **144**(3), 04017072.
- Li, Y., Wang, L., Li, Q., Wang, S. & Xu, M. (2025), ‘Experimental study on flow structure characteristics behind quasi-flexible vegetation patches’, *Physics of Fluids* **37**(12), 125103.
- Li, Y., Wang, Y., Anim, D. O., Tang, C., Du, W., Ni, L., Yu, Z. & Acharya, K. (2014), ‘Flow characteristics in different densities of submerged flexible vegetation from an open-channel flume study of artificial plants’, *Geomorphology* **204**, 314–324.
- Liang, X., Wang, Y. & Lei, J. (2025), ‘The evolution of hydrodynamic intensities and sediment erosion along submerged aquatic vegetation’, *Water Resources Research* **61**(3), e2024WR038311.
- Lightbody, A. F. & Nepf, H. M. (2006), ‘Prediction of velocity profiles and longitudinal dispersion in salt marsh vegetation’, *Limnology and Oceanography* **51**(1), 218–228.
- Liu, C., Hu, Z., Lei, J. & Nepf, H. (2018), ‘Vortex structure and sediment deposition in the wake behind a finite patch of model submerged vegetation’, *Journal of Hydraulic Engineering* **144**(2), 04017065.
- Liu, C. & Nepf, H. (2016), ‘Sediment deposition within and around a finite patch of model vegetation over a range of channel velocity’, *Water Resources Research* **52**(1), 600–612.
- Liu, C. & Shan, Y. (2019), ‘Analytical model for predicting the longitudinal profiles of velocities in a channel with a model vegetation patch’, *Journal of Hydrology* **576**, 561–574.
- Liu, C., Shan, Y., He, L., Li, F., Liu, X. & Nepf, H. (2024), ‘Plant morphology impacts bedload sediment transport’, *Geophysical Research Letters* **51**(12), e2024GL108800.
- Liu, C., Shan, Y., Li, F., Liu, X. & Nepf, H. (2025), ‘Submerged flexible canopies produce weaker shear-layer turbulence and mitigate sediment transport, compared to rigid model canopies’, *Geophysical Research Letters* **52**(23), e2025GL117007.

- Liu, C., Shan, Y. & Nepf, H. (2021), ‘Impact of stem size on turbulence and sediment resuspension under unidirectional flow’, *Water Resources Research* **57**(3), e2020WR028620.
- Liu, C., Shan, Y., Sun, W., Yan, C. & Yang, K. (2020), ‘An open channel with an emergent vegetation patch: Predicting the longitudinal profiles of velocities based on exponential decay’, *Journal of Hydrology* **582**, 124429.
- Liu, C., Yan, C., Sun, S., Lei, J., Nepf, H. & Shan, Y. (2022), ‘Velocity, turbulence, and sediment deposition in a channel partially filled with a phragmites australis canopy’, *Water Resources Research* **58**(8), e2022WR032381.
- Liu, D., Diplas, P., Fairbanks, J. D. & Hodges, C. C. (2008), ‘An experimental study of flow through rigid vegetation’, *Journal of Geophysical Research: Earth Surface* **113**(F4), F04015.
- Liu, M., Huai, W. & Ji, B. (2021), ‘Characteristics of the flow structures through and around a submerged canopy patch’, *Physics of Fluids* **33**(3), 035144.
- Liu, M., Huai, W., Tang, H., Wang, Y. & Yuan, S. (2024), ‘Numerical study of mean and turbulent flow adjustments in open channels with limited near-bank vegetation patches’, *Physics of Fluids* **36**(9), 095117.
- Lockwood, B. & Drakeford, B. M. (2021), ‘The value of carbon sequestration by saltmarsh in chichester harbour, united kingdom’, *Journal of Environmental Economics and Policy* **10**(3), 278–292.
- Lorenz, S., Pusch, M. T. & Blaschke, U. (2015), ‘Minimum shoreline restoration requirements to improve the ecological status of a north-eastern german glacial lowland lake in an urban landscape’, *Fundamental and Applied Limnology* **186**(4), 323–332.
- Lu, Y., Cheng, N.-S., Wei, M. & Ancey, C. (2024), Vegetation submergence effects on bedload transport rate, in ‘EGU General Assembly Conference Abstracts’, p. 9559.
- Luhar, M., Coutu, S., Infantes, E., Fox, S. & Nepf, H. (2010), ‘Wave-induced velocities inside a model seagrass bed’, *Journal of Geophysical Research: Oceans* **115**(C12), C12005.
- Luhar, M. & Nepf, H. (2016), ‘Wave-induced dynamics of flexible blades’, *Journal of Fluids and Structures* **61**, 20–41.
- Luhar, M. & Nepf, H. M. (2011), ‘Flow-induced reconfiguration of buoyant and flexible aquatic vegetation’, *Limnology and Oceanography* **56**(6), 2003–2017.
- Luhar, M., Rominger, J. & Nepf, H. (2008), ‘Interaction between flow, transport and vegetation spatial structure’, *Environmental Fluid Mechanics* **8**, 423–439.

- López, F. & García, M. (1998), ‘open-channel flow through simulated vegetation: Suspended sediment transport modeling’, *Water Resources Research* **34**(9), 2341–2352.
- Malothu, A., Afzal, M. S., Penna, N., Padhi, E., Gaudio, R. & Dey, S. (2025), ‘Hydrodynamics of a rigid submerged vegetated flow’, *Physics of Fluids* **37**(4), 045151.
- Mandel, T. L., Gakhar, S., Chung, H., Rosenzweig, I. & Koseff, J. R. (2019), ‘On the surface expression of a canopy-generated shear instability’, *Journal of Fluid Mechanics* **867**, 633–660.
- Marjoribanks, T. I., Lague, D., Hardy, R. J., Boothroyd, R. J., Leroux, J., Mony, C. & Puijalon, S. (2019), ‘Flexural rigidity and shoot reconfiguration determine wake length behind salt-marsh vegetation patches’, *Journal of Geophysical Research: Earth Surface* **124**(8), 2176–2196.
- Martino, R., Paterson, A. & Piva, M. (2012), ‘Double-average mean flow and local turbulence intensity profiles from piv measurements for an open channel flow with rigid vegetation’, *Environmental Fluid Mechanics* **12**(1), 45–62.
- Matsumoto, K., Okamoto, T.-a., Sanjou, M., Marjoribanks, T. I. & Takada, M. (2025), ‘Secondary flow structure and sediment deposition around flexible and rigid vegetation patches’, *Physics of Fluids* **37**(2), 025204.
- Maza, M., Adler, K., Ramos, D., Garcia, A. M. & Nepf, H. (2017), ‘Velocity and drag evolution from the leading edge of a model mangrove forest’, *Journal of Geophysical Research: Oceans* **122**(11), 9144–9159.
- McKenna Neuman, C. & Bédard, O. (2015), ‘A wind tunnel study of flow structure adjustment on deformable sand beds containing a surface-mounted obstacle’, *Journal of Geophysical Research: Earth Surface* **120**(9), 1824–1840.
- Medjnoun, T., Vanderwel, C. & Ganapathisubramani, B. (2020), ‘Effects of heterogeneous surface geometry on secondary flows in turbulent boundary layers’, *Journal of Fluid Mechanics* **886**, A31.
- Meire, D. W. S. A., Kondziolka, J. M. & Nepf, H. M. (2014), ‘Interaction between neighboring vegetation patches: Impact on flow and deposition’, *Water Resources Research* **50**(5), 3809–3825.
- Meng, Z.-K., Wang, P., Liu, Y. & Zeng, L. (2025), ‘Flow characteristics and velocity prediction considering changes in frontal area of submerged flexible vegetation’, *Journal of Hydrology* p. 133846.

- Minderhoud, P. S. J., Coumou, L., Erkens, G., Middelkoop, H. & Stouthamer, E. (2019), 'Mekong delta much lower than previously assumed in sea-level rise impact assessments', *Nature communications* **10**(1), 3847.
- Mofrad, M. R. T., Afzalimehr, H., Parvizi, P. & Ahmad, S. (2023), 'Comparison of velocity and reynolds stress distributions in a straight rectangular channel with submerged and emergent vegetation', *Water* **15**(13).
- Monti, A., Omidyeganeh, M., Eckhardt, B. & Pinelli, A. (2020), 'On the genesis of different regimes in canopy flows: a numerical investigation', *Journal of Fluid Mechanics* **891**, A9.
- Mu, H. & Fu, S. (2023), 'Comparison of the influences of vegetation stem parameters on hydraulic variables and sediment transport capacity', *International Soil and Water Conservation Research* **11**(1), 135–144.
- Muzzammil, M. & Gangadhariah, T. (2003), 'The mean characteristics of horseshoe vortex at a cylindrical pier', *Journal of Hydraulic Research* **41**(3), 285–297.
- Métivier, F., Paola, C., Kozarek, J. L. & Tal, M. (2016), *Experimental studies and practical challenges in fluvial geomorphology*, John Wiley & Sons, Ltd, chapter 20, pp. 456–475.
- Nagelkerken, I., Herman, P. M. J., Bouma, T. J., Katwijk, M. M. v., Gillis, L. G., Ziegler, A. D., Jones, C. G. & Jeuken, C. J. L. (2014), 'Potential for landscape-scale positive interactions among tropical marine ecosystems', *Marine Ecology Progress Series* **503**, 289–303. 10.3354/meps10716.
- Nair, A., Kazemi, A., Curet, O. & Verma, S. (2023), 'Porous cylinder arrays for optimal wake and drag characteristics', *Journal of Fluid Mechanics* **961**, A18.
- Narayana, P. L., Timbadiya, P. V. & Patel, P. L. (2022), 'Vorticity fields around a pier on rigid and mobile bed channels', *ISH Journal of Hydraulic Engineering* **28**(4), 400–409.
- Nardin, W., Larsen, L., Fagherazzi, S. & Wiberg, P. (2018), 'Tradeoffs among hydrodynamics, sediment fluxes and vegetation community in the virginia coast reserve, usa', *Estuarine, Coastal and Shelf Science* **210**, 98–108.
- Neary, V. S., Constantinescu, S. G., Bennett, S. J. & Diplas, P. (2012), 'Effects of vegetation on turbulence, sediment transport, and stream morphology', *Journal of Hydraulic Engineering* **138**(9), 765–776.
- Nepf, H. (2012a), 'Hydrodynamics of vegetated channels', *Journal of Hydraulic Research* **50**(3), 262–279.



- Nepf, H., Ghisalberti, M., White, B. & Murphy, E. (2007), 'Retention time and dispersion associated with submerged aquatic canopies', *Water Resources Research* **43**(4).
- Nepf, H. M. (1999), 'Drag, turbulence, and diffusion in flow through emergent vegetation', *Water Resources Research* **35**(2), 479–489.
- Nepf, H. M. (2012b), 'Flow and transport in regions with aquatic vegetation', *Annual Review of Fluid Mechanics* **44**(1), 123–142.
- Nepf, H. M., Sullivan, J. A. & Zavistoski, R. A. (1997), 'A model for diffusion within emergent vegetation', *Limnology and Oceanography* **42**(8), 1735–1745.
- Nepf, H. M. & Vivoni, E. R. (2000), 'Flow structure in depth-limited, vegetated flow', *Journal of Geophysical Research: Oceans* **105**(C12), 28547–28557.
- Nezu, I., Nakagawa, H. & Jirka, G. H. (1994), 'Turbulence in open channel flows', *Journal of Hydraulic Engineering* **120**(10), 1235–1237.
- Nezu, I. & Onitsuka, K. (2001), 'Turbulent structures in partly vegetated open-channel flows with  $l_{da}$  and  $\pi v$  measurements', *Journal of Hydraulic Research* **39**(6), 629–642.
- Nezu, I. & Sanjou, M. (2008), 'Turbulence structure and coherent motion in vegetated canopy open-channel flows', *Journal of Hydro-environment Research* **2**(2), 62–90.
- Nicolai, C., Taddei, S., Manes, C. & Ganapathisubramani, B. (2020), 'Wakes of wall-bounded turbulent flows past patches of circular cylinders', *Journal of Fluid Mechanics* **892**, A37.
- Nicolle, A. & Eames, I. (2011), 'Numerical study of flow through and around a circular array of cylinders', *Journal of Fluid Mechanics* **679**, 1–31.
- Ninto, Y. & Garcia, M. H. (1996), 'Experiments on particle—turbulence interactions in the near-wall region of an open channel flow: implications for sediment transport', *Journal of Fluid Mechanics* **326**, 285–319.
- Nittrouer, J. A., Best, J. L., Brantley, C., Cash, R. W., Czapiga, M., Kumar, P. & Parker, G. (2012), 'Mitigating land loss in coastal louisiana by controlled diversion of mississippi river sand', *Nature Geoscience* **5**(8), 534–537.
- Norris, B. K., Mullarney, J. C., Bryan, K. R. & Henderson, S. M. (2021), 'Relating millimeter-scale turbulence to meter-scale subtidal erosion and accretion across the fringe of a coastal mangrove forest', *Earth Surface Processes and Landforms* **46**(3), 573–592.
- Nowacki, D. J., Beudin, A. & Ganju, N. K. (2017), 'Spectral wave dissipation by submerged aquatic vegetation in a back-barrier estuary', *Limnology and Oceanography* **62**(2), 736–753.

- Okamoto, T.-A. & Nezu, I. (2009), ‘Turbulence structure and “monami” phenomena in flexible vegetated open-channel flows’, *Journal of Hydraulic Research* **47**(6), 798–810.
- Okamoto, T.-a. & Nezu, I. (2013), ‘Spatial evolution of coherent motions in finite-length vegetation patch flow’, *Environmental Fluid Mechanics* **13**(5), 417–434.
- Okamoto, T., Nezu, I. & Sanjou, M. (2016), ‘Flow–vegetation interactions: length-scale of the “monami” phenomenon’, *Journal of Hydraulic Research* **54**(3), 251–262.
- Okhravi, S., Gohari, S., Alemi, M. & Maia, R. (2023), ‘Numerical modeling of local scour of non-uniform graded sediment for two arrangements of pile groups’, *International Journal of Sediment Research* **38**(4), 597–614.
- Okubo, A. (1970), ‘Horizontal dispersion of floatable particles in the vicinity of velocity singularities such as convergences’, *Deep Sea Research and Oceanographic Abstracts* **17**(3), 445–454.
- Oorschot, M. v., Kleinhans, M., Geerling, G. & Middelkoop, H. (2016), ‘Distinct patterns of interaction between vegetation and morphodynamics’, *Earth Surface Processes and Landforms* **41**(6), 791–808.
- Orth, R. J., Lefcheck, J. S., McGlathery, K. S., Aoki, L., Luckenbach, M. W., Moore, K. A., Oreska, M. P. J., Snyder, R., Wilcox, D. J. & Lusk, B. (2020), ‘Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services’, *Science Advances* **6**(41), eabc6434.
- Ortiz, A. C., Ashton, A. & Nepf, H. (2013), ‘Mean and turbulent velocity fields near rigid and flexible plants and the implications for deposition’, *Journal of Geophysical Research: Earth Surface* **118**(4), 2585–2599.
- O’Hare, M. T., McGahey, C., Bissett, N., Cailles, C., Henville, P. & Scarlett, P. (2010), ‘Variability in roughness measurements for vegetated rivers near base flow, in england and scotland’, *Journal of Hydrology* **385**(1), 361–370.
- O’Hare, M. T., Stillman, R. A., McDonnell, J. & Wood, L. R. (2007), ‘Effects of mute swan grazing on a keystone macrophyte’, *Freshwater Biology* **52**(12), 2463–2475.
- Paola, C., Twilley, R. R., Edmonds, D. A., Kim, W., Mohrig, D., Parker, G., Viparelli, E. & Voller, V. R. (2011), ‘Natural processes in delta restoration: Application to the mississippi delta’, *Annual Review of Marine Science* **3**(Volume 3, 2011), 67–91.
- Park, H. & Hwang, J. H. (2019), ‘Quantification of vegetation arrangement and its effects on longitudinal dispersion in a channel’, *Water Resources Research* **55**(5), 4488–4498.

- Park, H., Lee, D., Jeon, W., Hahn, S., Kim, J., Kim, J., Choi, J. & Choi, H. (2006), 'Drag reduction in flow over a two-dimensional bluff body with a blunt trailing edge using a new passive device', *Journal of Fluid Mechanics* **563**, 389–414.
- Park, H. & Nepf, H. (2025a), 'Bedload transport within a patchy submerged canopy with different patch densities and spatial configuration', *Frontiers in Marine Science* **12**, 1531231.
- Park, H. & Nepf, H. (2025b), 'Turbulence in a channel with a patchy submerged canopy: the impact of spatial configuration', *Journal of Fluid Mechanics* **1006**, A15.
- Patil, S. & Singh, V. P. (2010), 'Characteristics of monami wave in submerged vegetated flow', *Journal of Hydrologic Engineering* **15**(3), 171–181.
- Peltier, Y. (2011), Physical modelling of overbank flows with a groyne set on the floodplain, PhD thesis, Université Claude Bernard-Lyon I.
- Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., Craft, C., Fourqurean, J. W., Kauffman, J. B., Marbà, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D. & Baldera, A. (2012), 'Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems', *PLOS ONE* **7**(9), 1–7.
- Peng, Y., Ouyang, J., Guan, M., Wang, B. & Rubinato, M. (2024), 'Experimental and numerical estimation of velocity and concentration distributions in partially vegetated open channels', *Journal of Hydrology* **628**, 130537.
- Penna, N., Coscarella, F., D'Ippolito, A. & Gaudio, R. (2022), 'Effects of fluvial instability on the bed morphology in vegetated channels', *Environmental Fluid Mechanics* **22**(2-3), 619–644.
- Peruzzo, P., Defina, A. & Nepf, H. (2012), 'Capillary trapping of buoyant particles within regions of emergent vegetation', *Water Resources Research* **48**(7).
- Pfeiffer, A. M., Collins, B. D., Anderson, S. W., Montgomery, D. R. & Istanbuluoglu, E. (2019), 'River bed elevation variability reflects sediment supply, rather than peak flows, in the uplands of washington state', *Water Resources Research* **55**(8), 6795–6810.
- Poggi, D., Porporato, A., Ridolfi, L., Albertson, J. & Katul, G. (2004), 'The effect of vegetation density on canopy sub-layer turbulence', *Boundary-Layer Meteorology* **111**, 565–587.
- Pollen, N., Simon, A. & Collison, A. (2004), 'Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability', *Riparian vegetation and fluvial geomorphology* **8**, 125–139.

- Pope, S. (2000), *Turbulent flows*, Cambridge university press.
- Proust, S., Fernandes, J. N., Leal, J. B., Rivière, N. & Peltier, Y. (2017), ‘Mixing layer and coherent structures in compound channel flows: Effects of transverse flow, velocity ratio, and vertical confinement’, *Water Resources Research* **53**(4), 3387–3406.
- Proust, S., Fernandes, J. N., Peltier, Y., Leal, J. B., Riviere, N. & Cardoso, A. H. (2013), ‘Turbulent non-uniform flows in straight compound open-channels’, *Journal of Hydraulic Research* **51**(6), 656–667.
- Proust, S. & Nikora, V. I. (2020), ‘Compound open-channel flows: effects of transverse currents on the flow structure’, *Journal of Fluid Mechanics* **885**, A24.
- Ptasinski, P. K., Boersma, B. J., Nieuwstadt, F. T. M., Hulsen, M. A., Van Den Brule, B. H. A. A. & Hunt, J. C. R. (2003), ‘Turbulent channel flow near maximum drag reduction: simulations, experiments and mechanisms’, *Journal of Fluid Mechanics* **490**, 251–291.
- Pujol, D., Colomer, J., Serra, T. & Casamitjana, X. (2010), ‘Effect of submerged aquatic vegetation on turbulence induced by an oscillating grid’, *Continental Shelf Research* **30**(9), 1019–1029.
- Qiang, Y., Duan, Y., Cao, L., Wang, Y., Zhu, D. & Li, D. (2025), ‘Effects of higher and lower angle isolated dunes on very-large-scale motions in open channel flows’, *Physics of Fluids* **37**(12), 125151.
- Rao, L., Wang, P.-f., Dai, Q.-s. & Wang, C. (2018), ‘The coupling between hydrodynamic and purification efficiencies of ecological porous spur-dike in field drainage ditch’, *Journal of Hydrodynamics* **30**(3), 373–383.
- Rathod, L. V., Timbadiya, P. V. & Barman, B. (2025), ‘Turbulent anisotropy and coherent structures in flow through a symmetric compound channel with emergent floodplain vegetation’, *Physics of Fluids* **37**(1), 015174.
- Raupach, M. R., Finnigan, J. J. & Brunet, Y. (1996), ‘Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy’, *Boundary-Layer Meteorology* pp. 375–395.
- Reid, H., Brierley, G., Mcfarlane, K., Coleman, S. & Trowsdale, S. (2013), ‘The role of landscape setting in minimizing hydrogeomorphic impacts of flow regulation’, *International Journal of Sediment Research* **28**(2), 149–161.
- Ren, B.-l., Wang, D., Li, W.-q. & Yang, K.-j. (2020), ‘The velocity patterns in rigid and mobile channels with vegetation patches’, *Journal of Hydrodynamics* **32**(3), 561–569.

- Ricardo, A. M., Franca, M. J. & Ferreira, R. M. L. (2016), 'Turbulent flows within random arrays of rigid and emergent cylinders with varying distribution', *Journal of Hydraulic Engineering* **142**(9), 04016022.
- Ricardo, A. M., Koll, K., Franca, M. J., Schleiss, A. J. & Ferreira, R. M. L. (2014), 'The terms of turbulent kinetic energy budget within random arrays of emergent cylinders', *Water Resources Research* **50**(5), 4131–4148.
- Riis, T., Kelly-Quinn, M., Aguiar, F. C., Manolaki, P., Bruno, D., Bejarano, M. D., Clerici, N., Fernandes, M. R., Franco, J. C., Pettit, N., Portela, A. P., Tammeorg, O., Tammeorg, P., Rodríguez-González, P. M. & Dufour, S. (2020), 'Global overview of ecosystem services provided by riparian vegetation', *BioScience* **70**(6), 501–514.
- Rinaldi, M. & Casagli, N. (1999), 'Stability of streambanks formed in partially saturated soils and effects of negative pore water pressures: the sieve river (italy)', *Geomorphology* **26**(4), 253–277.
- Rodrigues, S., Bréhéret, J.-G., Macaire, J.-J., Moatar, F., Nistoran, D. & Jugé, P. (2006), 'Flow and sediment dynamics in the vegetated secondary channels of an anabranching river: The loire river (france)', *Sedimentary Geology* **186**(1), 89–109.
- Rominger, J. T., Lightbody, A. F. & Nepf, H. M. (2010), 'Effects of added vegetation on sand bar stability and stream hydrodynamics', *Journal of Hydraulic Engineering* **136**(12), 994–1002.
- Rominger, J. T. & Nepf, H. M. (2011), 'Flow adjustment and interior flow associated with a rectangular porous obstruction', *Journal of Fluid Mechanics* **680**, 636–659.
- Roshko, A. (1961), 'Experiments on the flow past a circular cylinder at very high reynolds number', *Journal of Fluid Mechanics* **10**(3), 345–356.
- Sabokrouhiyeh, N., Bottacin-Busolin, A., Tregnaghi, M., Nepf, H. & Marion, A. (2020), 'Variation in contaminant removal efficiency in free-water surface wetlands with heterogeneous vegetation density', *Ecological Engineering* **143**, 105662.
- Sahin, M. & Owens, R. G. (2004), 'A numerical investigation of wall effects up to high blockage ratios on two-dimensional flow past a confined circular cylinder', *Physics of Fluids* **16**(5), 1305–1320.
- Saiers, J. E., Harvey, J. W. & Mylon, S. E. (2003), 'Surface-water transport of suspended matter through wetland vegetation of the florida everglades', *Geophysical Research Letters* **30**(19).

- Sand-jensen, K. (1998), 'Influence of submerged macrophytes on sediment composition and near-bed flow in lowland streams', *Freshwater Biology* **39**(4), 663–679.
- Sand-Jensen, K. & Madsen, T. (1992), 'Patch dynamics of the stream macrophyte, callitriche cophocarpa', *Freshwater Biology* **27**(2), 277–282.
- Savio, M., Vettori, D., Biggs, H., Zampiron, A., Cameron, S. M., Stewart, M., Soulsby, C. & Nikora, V. (2023), 'Hydraulic resistance of artificial vegetation patches in aligned and staggered configurations', *Journal of Hydraulic Research* **61**(2), 220–232.
- Schewe, G. (1983), 'On the force fluctuations acting on a circular cylinder in crossflow from subcritical up to transcritical reynolds numbers', *Journal of Fluid Mechanics* **133**, 265–285.
- Shan, Y., Liu, C. & Nepf, H. (2019), 'Comparison of drag and velocity in model mangrove forests with random and in-line tree distributions', *Journal of Hydrology* **568**, 735–746.
- Shan, Y., Yan, C., Liu, J. & Liu, C. (2023), 'Predicting velocity and turbulent kinetic energy inside an emergent phragmites australis canopy with real morphology', *Environmental Fluid Mechanics* **23**(4), 943–963.
- Shan, Y., Zhao, T., Liu, C. & Nepf, H. (2020), 'Turbulence and bed load transport in channels with randomly distributed emergent patches of model vegetation', *Geophysical Research Letters* **47**(12), e2020GL087055.
- Shi, H., Zhang, J. & Huai, W. (2023), 'Experimental study on velocity distributions, secondary currents, and coherent structures in open channel flow with submerged riparian vegetation', *Advances in Water Resources* **173**, 104406.
- Shi, Y., Jiang, B. & Nepf, H. M. (2016), 'Influence of particle size and density, and channel velocity on the deposition patterns around a circular patch of model emergent vegetation', *Water Resources Research* **52**(2), 1044–1055.
- Shi, Z., Pethick, J. S. & Pye, K. (1995), 'Flow structure in and above the various heights of a saltmarsh canopy: A laboratory flume study', *Journal of Coastal Research* **11**(4), 1204–1209.
- Shih, W. & Diplas, P. (2018), 'A unified approach to bed load transport description over a wide range of flow conditions via the use of conditional data treatment', *Water Resources Research* **54**(5), 3490–3509.
- Shui, Q., Duan, C., Wang, D. & Gu, Z. (2021), 'New insights into numerical simulations of flow around two tandem square cylinders', *AIP Advances* **11**(4).

- Simon, A. & Collison, A. J. C. (2002), 'Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability', *Earth Surface Processes and Landforms* **27**(5), 527–546.
- Song, S.-Y., Wang, X.-K., Duan, H.-F., Stocchino, A. & Yan, X.-F. (2024), 'Numerical investigation of a three-dimensional flow structure influenced by the lateral expansion of a partially distributed submerged canopy', *Physics of Fluids* **36**(8), 085164.
- Song, Y., Liu, R., Yang, Q., Li, J., Cai, C., Feng, Y., Huang, G., Hao, R., Li, H., Zhan, C. & Wen, X. (2024), 'Effects of patch properties of submerged vegetation on sediment scouring and deposition', *Water* **16**(15).
- Sonnenwald, F., Guymer, I. & Stovin, V. (2019), 'A cfd-based mixing model for vegetated flows', *Water Resources Research* **55**(3), 2322–2347.
- Sousa, W. T. Z., Thomaz, S. M. & Murphy, K. J. (2010), 'Response of native egeria najas planch. and invasive hydrilla verticillata (l.f.) royle to altered hydroecological regime in a subtropical river', *Aquatic Botany* **92**(1), 40–48.
- Stocchino, A., Besio, G., Angiolani, S. & Brocchini, M. (2011), 'Lagrangian mixing in straight compound channels', *Journal of Fluid Mechanics* **675**, 168–198.
- Stocchino, A. & Brocchini, M. (2010), 'Horizontal mixing of quasi-uniform straight compound channel flows', *Journal of Fluid Mechanics* **643**, 425–435.
- Stroh, A., Schäfer, K., Frohnäpfel, B. & Forooghi, P. (2020), 'Rearrangement of secondary flow over spanwise heterogeneous roughness', *Journal of Fluid Mechanics* **885**, R5.
- Sukhodolov, A. N. & Sukhodolova, T. A. (2010), 'Case study: Effect of submerged aquatic plants on turbulence structure in a lowland river', *Journal of Hydraulic Engineering* **136**(7), 434–446.
- Sun, S., Shan, Y., Yan, C. & Liu, C. (2023), 'Impact of sediment size, channel velocity and plant density on sediment deposition inside phragmites australis canopies', *Journal of Hydrology* **626**, 130151.
- Suresh, D. B., Wood, D. & Jin, Y. (2025), 'Sedimentary bed morphology in the wake of flexible aquatic vegetation', *Water Science and Engineering*.
- Taddei, S., Manes, C. & Ganapathisubramani, B. (2016), 'Characterisation of drag and wake properties of canopy patches immersed in turbulent boundary layers', *Journal of Fluid Mechanics* **798**, 27–49.

- Tal, M. & Paola, C. (2010), 'Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments', *Earth Surface Processes and Landforms* **35**(9), 1014–1028.
- Tang, C., Jia, H., Zhang, S., Yi, Y. & Dey, S. (2025), 'Hydrodynamics of turbulent flow in channels with submerged flexible vegetation canopy', *Physics of Fluids* **37**(3), 032123.
- Tang, C., Yi, Y., Jia, W. & Zhang, S. (2020), 'Velocity and turbulence evolution in a flexible vegetation canopy in open channel flows', *Journal of Cleaner Production* **270**, 122543.
- Tang, C., Yi, Y. & Zhang, S. (2023), 'Flow and turbulence in unevenly obstructed channels with rigid and flexible vegetation', *Journal of Environmental Management* **326**, 116736.
- Tang, H., Wang, H., Liang, D., Lv, S. & Yan, L. (2013), 'Incipient motion of sediment in the presence of emergent rigid vegetation', *Journal of Hydro-environment Research* **7**(3), 202–208.
- Tang, X., Singh, P. K. & Rahimi, H. (2025), 'A semi-analytical model for the velocity profile in an open channel with suspended rigid vegetation', *Journal of Hydrology* **662**, 133856.
- Tanino, Y. & Nepf, H. M. (2008a), 'Laboratory investigation of mean drag in a random array of rigid, emergent cylinders', *Journal of Hydraulic Engineering* **134**(1), 34–41.
- Tanino, Y. & Nepf, H. M. (2008b), 'Lateral dispersion in random cylinder arrays at high reynolds number', *Journal of Fluid Mechanics* **600**, 339–371.
- Temmerman, S., Bouma, T., Van de Koppel, J., Van der Wal, D., De Vries, M. & Herman, P. (2007), 'Vegetation causes channel erosion in a tidal landscape', *Geology* **35**(7), 631–634.
- Temmink, R. J. M., Lamers, L. P. M., Angelini, C., Bouma, T. J., Fritz, C., van de Koppel, J., Lexmond, R., Rietkerk, M., Silliman, B. R., Joosten, H. & van der Heide, T. (2022), 'Recovering wetland biogeomorphic feedbacks to restore the world's biotic carbon hotspots', *Science* **376**(6593), eabn1479.
- Tinoco, R. O. & Coco, G. (2016), 'A laboratory study on sediment resuspension within arrays of rigid cylinders', *Advances in Water Resources* **92**, 1–9.
- Tinoco, R. O. & Coco, G. (2018), 'Turbulence as the main driver of resuspension in oscillatory flow through vegetation', *Journal of Geophysical Research: Earth Surface* **123**(5), 891–904.
- Tranmer, A. W., Ji, U., Ahn, M., Jung, S. H. & Yager, E. M. (2024), 'Characterizing erosion and deposition in and around riparian vegetation patches: Complex flow hydraulics, sediment supply, and morphodynamic feedbacks', *Water Resources Research* **60**(2), e2023WR034859.



- Truong, S. H., Uijttewaalt, W. S. J. & Stive, M. J. F. (2019), 'Exchange processes induced by large horizontal coherent structures in floodplain vegetated channels', *Water Resources Research* **55**(3), 2014–2032.
- Tschisgale, S., Löhrer, B., Meller, R. & Fröhlich, J. (2021), 'Large eddy simulation of the fluid–structure interaction in an abstracted aquatic canopy consisting of flexible blades', *Journal of Fluid Mechanics* **916**, A43.
- Tseng, C.-Y. & Tinoco, R. O. (2021), 'A two-layer turbulence-based model to predict suspended sediment concentration in flows with aquatic vegetation', *Geophysical Research Letters* **48**(3), e2020GL091255.
- Tsujimoto, T. (1999), 'Fluvial processes in streams with vegetation', *Journal of Hydraulic Research* **37**(6), 789–803.
- Uijttewaalt, W. S. J. & Booij, R. (2000), 'Effects of shallowness on the development of free-surface mixing layers', *Physics of Fluids* **12**(2), 392–402.
- Unigarro Villota, S., Ghisalberti, M., Philip, J. & Branson, P. (2023), 'Characterizing the three-dimensional flow in partially vegetated channels', *Water Resources Research* **59**(1), e2022WR032570.
- Valiela, I., Teal, J. M. & Deuser, W. G. (1978), 'The nature of growth forms in the salt marsh grass *spartina alterniflora*', *The American Naturalist* **112**(985), 461–470.
- van Dijk, W. M., Teske, R., van de Lageweg, W. I. & Kleinhans, M. G. (2013), 'Effects of vegetation distribution on experimental river channel dynamics', *Water Resources Research* **49**(11), 7558–7574.
- van Katwijk, M., Bos, A., Hermus, D. & Suykerbuyk, W. (2010), 'Sediment modification by seagrass beds: Muddification and sandification induced by plant cover and environmental conditions', *Estuarine, Coastal and Shelf Science* **89**(2), 175–181.
- van Prooijen, B. C. & Uijttewaalt, W. S. J. (2002), 'A linear approach for the evolution of coherent structures in shallow mixing layers', *Physics of Fluids* **14**(12), 4105–4114.
- Vandenbruwaene, W., Temmerman, S., Bouma, T. J., Klaassen, P. C., de Vries, M. B., Callaghan, D. P., van Steeg, P., Dekker, F., van Duren, L. A., Martini, E., Balke, T., Biermans, G., Schoelynck, J. & Meire, P. (2011), 'Flow interaction with dynamic vegetation patches: Implications for biogeomorphic evolution of a tidal landscape', *Journal of Geophysical Research: Earth Surface* **116**(F1), F01008.

- Vargas-Luna, A., Duró, G., Crosato, A. & Uijttewaal, W. (2019), ‘Morphological adaptation of river channels to vegetation establishment: A laboratory study’, *Journal of Geophysical Research: Earth Surface* **124**(7), 1981–1995.
- Vollmer, S. & Kleinhans, M. G. (2007), ‘Predicting incipient motion, including the effect of turbulent pressure fluctuations in the bed’, *Water Resources Research* **43**(5).
- Västilä, K., Järvelä, J. & Koivusalo, H. (2016), ‘Flow-vegetation-sediment interaction in a cohesive compound channel’, *Journal of Hydraulic Engineering* **142**(1), 04015034.
- Wang, D., Li, F. & Yang, K. (2023), ‘Effects of patch density and incoming sediment on flow characteristics and bed morphology’, *Water* **15**(18).
- Wang, H., Tang, H., Zhao, H., Zhao, X. & Lü, S. (2015), ‘Incipient motion of sediment in presence of submerged flexible vegetation’, *Water Science and Engineering* **8**(1), 63–67.
- Wang, J., He, G., Dey, S. & Fang, H. (2022a), ‘Fluid–structure interaction in a flexible vegetation canopy in an open channel’, *Journal of Fluid Mechanics* **951**, A41.
- Wang, J., He, G., Dey, S. & Fang, H. (2022b), ‘Influence of submerged flexible vegetation on turbulence in an open-channel flow’, *Journal of Fluid Mechanics* **947**, A31.
- Wang, J., He, G., Huang, L., Dey, S. & Fang, H. (2023), ‘Effects of submerged flexible vegetation on scalar transport in an open-channel flow’, *Water Resources Research* **59**(9), e2022WR034235.
- Wang, J., He, G., Huang, L., Dey, S. & Fang, H. (2024), ‘Drag force on submerged flexible vegetation in an open-channel flow’, *Water Resources Research* **60**(10), e2023WR036879.
- Wang, P.-f., Wang, C. & Zhu, D. Z. (2010), ‘Hydraulic resistance of submerged vegetation related to effective height’, *Journal of Hydrodynamics* **22**, 265–273.
- Wang, W.-J., Peng, W.-Q., Huai, W.-X., Katul, G. G., Liu, X.-B., Qu, X.-D. & Dong, F. (2019), ‘Friction factor for turbulent open channel flow covered by vegetation’, *Scientific Reports* **9**(1), 5178.
- Wang, W.-J., Zhao, Y.-F., Ren, S., Liu, X.-B., Dong, F., Li, J.-J., Fan, J.-J. & Wu, W.-Q. (2023), ‘Analytical solutions of flow velocity profile based on the morphological response of flexible vegetation’, *Journal of Hydrology* **624**, 129839.
- Wang, X., Chen, J., Zhou, B., Li, Y. & Xiang, Q. (2021), ‘Experimental investigation of flow past a confined bluff body: Effects of body shape, blockage ratio and reynolds number’, *Ocean Engineering* **220**, 108412.

- Wang, X., Li, S., Yang, Z.-h. & Huai, W.-x. (2022), ‘Incipient sediment motion in vegetated open-channel flows predicted by critical flow velocity’, *Journal of Hydrodynamics* **34**(1), 63–68.
- Wang, Z.-R., Zhang, S.-J., Jiang, Y.-X., Yao, Z.-D. & Yan, X.-F. (2024), ‘Evaluating shallow mixing layer in partially-distributed canopy flows using da-les: bed friction, water shallowness and canopy denseness’, *Engineering Applications of Computational Fluid Mechanics* **18**(1), 2298075.
- Waters, K. A. & Crowe Curran, J. (2016), ‘Effects of an emergent vegetation patch on channel reach bathymetry and stability during repeated unsteady flows’, *Water Resources Research* **52**(11), 9066–9085.
- Waycott, M., Duarte, C. M., Carruthers, T. J. B., Orth, R. J., Dennison, W. C., Olyarnik, S., Calladine, A., Fourqurean, J. W., Heck, K. L., Hughes, A. R., Kendrick, G. A., Kenworthy, W. J., Short, F. T. & Williams, S. L. (2009), ‘Accelerating loss of seagrasses across the globe threatens coastal ecosystems’, *Proceedings of the National Academy of Sciences* **106**(30), 12377–12381.
- Weiss, J. (1991), ‘The dynamics of enstrophy transfer in two-dimensional hydrodynamics’, *Physica D: Nonlinear Phenomena* **48**(2), 273–294.
- Welch, P. (1967), ‘The use of fast fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms’, *IEEE Transactions on audio and electroacoustics* **15**(2), 70–73.
- White, B. L. & Nepf, H. M. (2007), ‘Shear instability and coherent structures in shallow flow adjacent to a porous layer’, *Journal of Fluid Mechanics* **593**, 1–32.
- White, B. L. & Nepf, H. M. (2008), ‘A vortex-based model of velocity and shear stress in a partially vegetated shallow channel’, *Water Resources Research* **44**(1), W01412.
- White, F. M. & Majdalani, J. (2006), *Viscous fluid flow*, Vol. 3, McGraw-Hill New York.
- Wilson, C. A. M. E., Stoesser, T., Bates, P. D. & Pinzen, A. B. (2003), ‘Open channel flow through different forms of submerged flexible vegetation’, *Journal of Hydraulic Engineering* **129**(11), 847–853.
- Wong, C. Y. H., Trinh, P. H. & Chapman, S. J. (2020), ‘Shear-induced instabilities of flows through submerged vegetation’, *Journal of Fluid Mechanics* **891**, A17.

- Xu, D., Liu, J.-n., Wu, Y.-f. & Ji, C.-n. (2022), 'Numerical investigation of the dynamics of flexible vegetations in turbulent open-channel flows', *Journal of Hydrodynamics* **34**(4), 681–699.
- Xu, G. D., Duan, W. Y. & Xu, W. H. (2017), 'The propulsion of two flapping foils with tandem configuration and vortex interactions', *Physics of Fluids* **29**(9), 097102.
- Xu, Y., Esposito, C. R., Beltrán-Burgos, M. & Nepf, H. M. (2022), 'Competing effects of vegetation density on sedimentation in deltaic marshes', *Nature communications* **13**(1), 4641.
- Xu, Y. & Nepf, H. (2020), 'Measured and predicted turbulent kinetic energy in flow through emergent vegetation with real plant morphology', *Water Resources Research* **56**(12), e2020WR027892.
- Xu, Z. X., Ye, C., Zhang, Y. Y., Wang, X. K. & Yan, X. F. (2019), '2d numerical analysis of the influence of near-bank vegetation patches on the bed morphological adjustment', *Environmental Fluid Mechanics* **20**, 707–738.
- Xue, W., Wu, S., Wu, X., Dai, J., Yand, Q. & Wand, F. (2017), 'Sediment incipient motion on movable bed in rigid vegetation environment', *Advances in Water Science* **28**(2017-6-849), 849.
- Yagci, O., Celik, M. F., Kitsikoudis, V., Ozgur Kirca, V., Hodoglu, C., Valyrakis, M., Duran, Z. & Kaya, S. (2016), 'Scour patterns around isolated vegetation elements', *Advances in Water Resources* **97**, 251–265.
- Yagci, O., Tschiesche, U. & Kabdasli, M. (2010), 'The role of different forms of natural riparian vegetation on turbulence and kinetic energy characteristics', *Advances in Water Resources* **33**(5), 601–614.
- Yagci, O., Yildirim, I., Celik, M., Kitsikoudis, V., Duran, Z. & Kirca, V. O. (2017), 'Clear water scour around a finite array of cylinders', *Applied Ocean Research* **68**, 114–129.
- Yagci, O., Özgür Kirca, V. S., Kitsikoudis, V., Wilson, C. A. M. E., Celik, M. F. & Sertkan, C. (2024), 'Experimental study on influence of different patterns of an emergent vegetation patch on the flow field and scour/deposition processes in the wake region', *Water Resources Research* **60**(1), e2023WR034978.
- Yager, E. M. & Schmeeckle, M. W. (2013), 'The influence of vegetation on turbulence and bed load transport', *Journal of Geophysical Research: Earth Surface* **118**(3), 1585–1601.

- Yamasaki, T. N., de Lima, P. H. S., Silva, D. F., Preza, C. G. d. A., Janzen, J. G. & Nepf, H. M. (2019), 'From patch to channel scale: The evolution of emergent vegetation in a channel', *Advances in Water Resources* **129**, 131–145.
- Yamasaki, T. N., Jiang, B., Janzen, J. G. & Nepf, H. M. (2021), 'Feedback between vegetation, flow, and deposition: A study of artificial vegetation patch development', *Journal of Hydrology* **598**, 126232.
- Yan, C., Shan, Y., Liu, C. & Liu, X. (2022), 'Analytical model for predicting the lateral profiles of velocities through a partially vegetated channel', *Journal of Hydrology* **612**, 128137.
- Yan, X. F., Duan, H. F., Wai, W. H. O., Li, C. W. & Wang, X. K. (2022), 'Spatial flow pattern, multi-dimensional vortices, and junction momentum exchange in a partially covered submerged canopy flume', *Water Resources Research* **58**(3), e2020WR029494.
- Yan, X.-F., Duan, H.-F., Wai, W.-H. O. & Wang, X.-K. (2023), 'Bed morphology adjustment under the impact of a near-bank emergent model vegetation patch', *Journal of Hydraulic Research* **61**(5), 735–753.
- Yan, X. F., Wai, W. H. O. & Li, C. W. (2016), 'Characteristics of flow structure of free-surface flow in a partly obstructed open channel with vegetation patch', *Environmental Fluid Mechanics* **16**(4), 807–832.
- Yang, J. Q., Chung, H. & Nepf, H. M. (2016), 'The onset of sediment transport in vegetated channels predicted by turbulent kinetic energy', *Geophysical Research Letters* **43**(21), 11,261–11,268.
- Yang, J. Q. & Nepf, H. M. (2018), 'A turbulence-based bed-load transport model for bare and vegetated channels', *Geophysical Research Letters* **45**(19), 10,428–10,436.
- Yang, J. Q. & Nepf, H. M. (2019), 'Impact of vegetation on bed load transport rate and bedform characteristics', *Water Resources Research* **55**(7), 6109–6124.
- Yang, L., Huai, W. & Guo, Y. (2021), 'Stochastic simulation of the suspended sediment deposition in the channel with vegetation and its relevance to turbulent kinetic energy', *Water Resources Research* **57**(9).
- Yang, W. & Choi, S.-U. (2009), 'Impact of stem flexibility on mean flow and turbulence structure in depth-limited open channel flows with submerged vegetation', *Journal of Hydraulic Research* **47**(4), 445–454.
- Yang, W. & Choi, S.-U. (2010), 'A two-layer approach for depth-limited open-channel flows with submerged vegetation', *Journal of Hydraulic Research* **48**(4), 466–475.

- Yarnell, S. M., Mount, J. F. & Larsen, E. W. (2006), 'The influence of relative sediment supply on riverine habitat heterogeneity', *Geomorphology* **80**(3), 310–324.
- Yi, Z., Sun, Y., Wang, X., Liu, D. & Yan, X. (2022), 'Numerical analysis of hydrodynamics influenced by a deformed bed due to a near-bank vegetation patch', *Water Supply* **22**(2), 1546–1556.
- Yu, W.-y., Jiang, C.-b., Shi, Y., Zhou, Q., Liu, J. & Zhang, Q. (2019), 'Experimental study of the impact of the floating-vegetation island on mean and turbulence structure', *Journal of Hydrodynamics* **31**, 922–930.
- Yu, Z., Shan, Y., Liu, C. & Liu, X. (2021), 'Wake flow and vortex structures behind emergent vegetation patches elongated in the longitudinal direction', *Journal of Hydrodynamics* **33**(6), 1148–1161.
- Yu, Z., Wang, D. & Liu, X. (2019), 'Impact of vegetation density on the wake structure', *Water* **11**(6).
- Zampogna, G. A., Pluvinage, F., Kourta, A. & Bottaro, A. (2016), 'Instability of canopy flows', *Water Resources Research* **52**(7), 5421–5432.
- Zhang, J. & Hu, R. (2023), 'Turbulence structure in an experimental compound channel with varying coverage of riparian vegetation on the floodplain', *Journal of Hydrology* **620**, 129378.
- Zhang, J., Lei, J., Huai, W. & Nepf, H. (2020), 'Turbulence and particle deposition under steady flow along a submerged seagrass meadow', *Journal of Geophysical Research: Oceans* **125**(5), e2019JC015985.
- Zhang, J., Mi, Z., Wang, W., Li, Z., Li, P., Xu, J., Li, J., Wang, H. & Wu, Z. (2024), 'An analytical study for predicting incipient motion velocity of sediments in ecological open channel flows', *Physics of Fluids* **36**(4), 046620.
- Zhang, Y., Cheng, J., Hassan, M. A., Wang, P. & Wu, Z. (2024), 'Drag coefficient of emergent vegetation in a shallow nonuniform flow over a mobile sand bed', *Water Resources Research* **60**(5), e2023WR036535.
- Zhang, Y.-H., Duan, H.-F., Yan, X.-F. & Stocchino, A. (2023), 'Experimental study on the combined effects of patch density and elongation on wake structure behind a rectangular porous patch', *Journal of Fluid Mechanics* **959**, A36.
- Zhang, Y.-H., Duan, H.-F., Yan, X.-F. & Stocchino, A. (2024), 'Quantifying wake dynamics subjected to stream vegetation patch elongation: The influence of patch-edge vortices', *Physics of Fluids* **36**(5), 055108.

- Zhang, Y., Jeppesen, E., Liu, X., Qin, B., Shi, K., Zhou, Y., Thomaz, S. M. & Deng, J. (2017), 'Global loss of aquatic vegetation in lakes', *Earth-Science Reviews* **173**, 259–265.
- Zhang, Y., Lai, X. & Jiang, J. (2016), 'The impact of plant morphology on flow structure: comparative analysis of two types of submerged flexible macrophyte', *Hydrological Sciences Journal* **61**(12), 2226–2236.
- Zhao, F., Huai, W. & Li, D. (2017), 'Numerical modeling of open channel flow with suspended canopy', *Advances in Water Resources* **105**, 132–143.
- Zhao, M., Cheng, L., An, H. & Tong, F. (2015), 'Flow and flow-induced vibration of a square array of cylinders in steady currents', *Fluid Dynamics Research* **47**(4), 045505.
- Zhao, T. & Nepf, H. (2024), 'Turbulence and bedload transport in submerged vegetation canopies', *Water Resources Research* **60**(12), e2024WR037694.
- Zhao, T. & Nepf, H. M. (2021), 'Turbulence dictates bedload transport in vegetated channels without dependence on stem diameter and arrangement', *Geophysical Research Letters* **48**(21), e2021GL095316.
- Zong, L. & Nepf, H. (2010), 'Flow and deposition in and around a finite patch of vegetation', *Geomorphology* **116**(3), 363–372.
- Zong, L. & Nepf, H. (2011), 'Spatial distribution of deposition within a patch of vegetation', *Water Resources Research* **47**(3), W03516.
- Zong, L. & Nepf, H. (2012), 'Vortex development behind a finite porous obstruction in a channel', *Journal of Fluid Mechanics* **691**, 368–391.

## **Appendix A**

### **Summary of experimental parameters.**



| Case    | $L$<br>(m) | $W$<br>(m) | $\Phi$ | $U_\infty$<br>(cm/s) | $U_{e1}$<br>(cm/s) | $U_{e2}$<br>(cm/s) | $U_1$<br>(cm/s) | $U_2$<br>(cm/s) | $L_1$<br>(m) | $-\overline{u'v'}$<br>(m <sup>2</sup> /s <sup>2</sup> ) | VK | KH |
|---------|------------|------------|--------|----------------------|--------------------|--------------------|-----------------|-----------------|--------------|---------------------------------------------------------|----|----|
| Case 1  | 1.00       | 0.09       | 0.007  | 7.8                  | 3.8                | 9.2                | 3.6             | 9.0             | 0.15         | 1.03E-04                                                | Y  | Y  |
| Case 2  | 1.20       | 0.09       | 0.007  | 7.8                  | 3.4                | 9.4                | 3.3             | 9.4             | 0.15         | 1.04E-04                                                | Y  | Y  |
| Case 3  | 1.40       | 0.09       | 0.007  | 7.8                  | 3.1                | 9.6                | 3.1             | 9.6             | 0.05         | 1.21E-04                                                | Y  | Y  |
| Case 4  | 1.60       | 0.09       | 0.007  | 7.8                  | 3.0                | 9.6                | 3.0             | 9.6             | 0.00         | 9.66E-05                                                | Y  | Y  |
| Case 5  | 1.80       | 0.09       | 0.007  | 7.9                  | 3.2                | 9.7                | 3.2             | 9.7             | 0.00         | 1.16E-04                                                | Y  | Y  |
| Case 6  | 2.00       | 0.09       | 0.007  | 7.9                  | 3.4                | 9.9                | 3.4             | 9.9             | 0.00         | 2.60E-04                                                | Y  | Y  |
| Case 7  | 0.10       | 0.09       | 0.009  | 8.0                  | 7.6                | 8.5                | 6.6             | 8.4             | 0.50         | 5.86E-05                                                | N  | N  |
| Case 8  | 0.20       | 0.09       | 0.009  | 8.0                  | 7.1                | 8.5                | 6.1             | 8.7             | 0.40         | 2.65E-05                                                | N  | N  |
| Case 9  | 0.60       | 0.09       | 0.009  | 8.0                  | 4.8                | 9.3                | 4.3             | 9.4             | 0.30         | 8.16E-05                                                | N  | Y  |
| Case 10 | 0.90       | 0.09       | 0.009  | 7.6                  | 3.5                | 9.2                | 3.2             | 9.3             | 0.15         | 1.35E-04                                                | Y  | Y  |
| Case 11 | 0.91       | 0.09       | 0.009  | 7.8                  | 3.5                | 9.3                | 3.2             | 9.3             | 0.14         | 1.57E-04                                                | Y  | Y  |
| Case 12 | 1.00       | 0.09       | 0.009  | 7.7                  | 3.3                | 9.4                | 3.1             | 9.3             | 0.15         | 1.41E-04                                                | Y  | Y  |
| Case 13 | 1.11       | 0.09       | 0.009  | 7.7                  | 3.0                | 9.5                | 3.0             | 9.4             | 0.09         | 1.27E-04                                                | Y  | Y  |
| Case 14 | 1.14       | 0.09       | 0.009  | 7.7                  | 2.9                | 9.4                | 2.9             | 9.4             | 0.06         | 1.90E-04                                                | Y  | Y  |
| Case 15 | 1.20       | 0.09       | 0.009  | 7.7                  | 2.9                | 9.5                | 2.9             | 9.5             | 0.05         | 1.37E-04                                                | Y  | Y  |
| Case 16 | 1.40       | 0.09       | 0.009  | 7.7                  | 2.9                | 9.6                | 2.9             | 9.6             | 0.00         | 1.64E-04                                                | Y  | Y  |
| Case 17 | 1.50       | 0.09       | 0.009  | 7.7                  | 2.9                | 9.7                | 2.9             | 9.7             | 0.00         | 1.67E-04                                                | Y  | Y  |
| Case 18 | 1.60       | 0.09       | 0.009  | 7.7                  | 2.9                | 9.7                | 2.9             | 9.7             | 0.00         | 1.96E-04                                                | Y  | Y  |
| Case 19 | 0.10       | 0.09       | 0.013  | 8.0                  | 7.6                | 8.3                | 6.6             | 8.5             | 0.50         | 3.71E-05                                                | N  | N  |
| Case 20 | 0.20       | 0.09       | 0.013  | 7.9                  | 7.1                | 8.8                | 5.8             | 8.5             | 0.50         | 5.64E-05                                                | N  | N  |
| Case 21 | 0.60       | 0.09       | 0.013  | 8.0                  | 4.5                | 9.4                | 3.9             | 9.5             | 0.30         | 8.53E-05                                                | N  | Y  |
| Case 22 | 0.66       | 0.09       | 0.013  | 8.0                  | 4.3                | 9.8                | 3.5             | 9.8             | 0.19         | 1.23E-04                                                | Y  | Y  |

|         |      |      |       |     |     |      |     |      |      |          |   |   |
|---------|------|------|-------|-----|-----|------|-----|------|------|----------|---|---|
| Case 23 | 0.70 | 0.09 | 0.013 | 8.0 | 3.8 | 9.6  | 3.3 | 9.6  | 0.15 | 1.18E-04 | Y | Y |
| Case 24 | 0.74 | 0.09 | 0.013 | 7.9 | 3.6 | 9.6  | 3.1 | 9.7  | 0.16 | 1.16E-04 | Y | Y |
| Case 25 | 0.76 | 0.09 | 0.013 | 7.9 | 3.5 | 9.6  | 3.0 | 9.6  | 0.14 | 1.09E-04 | Y | Y |
| Case 26 | 0.80 | 0.09 | 0.013 | 7.9 | 3.4 | 9.7  | 3.0 | 9.7  | 0.15 | 1.32E-04 | Y | Y |
| Case 27 | 0.82 | 0.09 | 0.013 | 7.9 | 3.1 | 9.7  | 2.9 | 9.7  | 0.08 | 1.42E-04 | Y | Y |
| Case 28 | 0.84 | 0.09 | 0.013 | 7.9 | 3.2 | 9.7  | 3.0 | 9.7  | 0.16 | 1.22E-04 | Y | Y |
| Case 29 | 0.90 | 0.09 | 0.013 | 8.0 | 3.0 | 10   | 2.8 | 9.9  | 0.10 | 1.33E-04 | Y | Y |
| Case 30 | 1.00 | 0.09 | 0.013 | 7.7 | 2.6 | 9.7  | 2.6 | 9.9  | 0.10 | 1.36E-04 | Y | Y |
| Case 31 | 1.20 | 0.09 | 0.013 | 8.0 | 2.4 | 10.1 | 2.4 | 10.1 | 0.00 | 1.95E-04 | Y | Y |
| Case 32 | 1.40 | 0.09 | 0.013 | 8.0 | 2.4 | 10.2 | 2.4 | 10.2 | 0.00 | 2.14E-04 | Y | Y |
| Case 33 | 0.10 | 0.21 | 0.013 | 8.0 | 7.9 | 8.7  | 6.9 | 8.8  | 1    | 6.05E-05 | N | Y |
| Case 34 | 0.20 | 0.21 | 0.013 | 7.9 | 7.2 | 9.2  | 6.3 | 9.3  | 0.9  | 7.08E-05 | N | Y |
| Case 35 | 0.60 | 0.21 | 0.013 | 8.0 | 5.8 | 10.8 | 4.6 | 10.7 | 0.8  | 1.09E-04 | N | Y |
| Case 36 | 1.00 | 0.21 | 0.013 | 8.0 | 4.4 | 11.9 | 3.3 | 11.2 | 0.5  | 1.04E-04 | N | Y |
| Case 37 | 1.40 | 0.21 | 0.013 | 8.0 | 3.3 | 12.2 | 2.6 | 11.9 | 0.4  | 1.26E-04 | N | Y |
| Case 38 | 0.10 | 0.09 | 0.02  | 8.0 | 5.2 | 8.6  | 4.7 | 8.7  | 0.20 | 5.66E-05 | N | N |
| Case 39 | 0.20 | 0.09 | 0.02  | 7.8 | 4.0 | 8.8  | 3.4 | 8.9  | 0.15 | 3.15E-05 | N | Y |
| Case 40 | 0.60 | 0.09 | 0.02  | 7.9 | 1.6 | 9.9  | 1.6 | 9.9  | 0.00 | 1.17E-04 | Y | Y |
| Case 41 | 1.00 | 0.09 | 0.02  | 7.9 | 2.0 | 10.2 | 2.0 | 10.2 | 0.00 | 1.72E-04 | Y | Y |
| Case 42 | 1.40 | 0.09 | 0.02  | 8.0 | 2.5 | 10.5 | 2.5 | 10.5 | 0.00 | 2.30E-04 | Y | Y |
| Case 43 | 0.10 | 0.09 | 0.04  | 8.1 | 4.5 | 9.1  | 3.2 | 9.3  | 0.30 | 6.23E-05 | N | Y |
| Case 44 | 0.16 | 0.09 | 0.04  | 8.0 | 4.3 | 9.5  | 2.5 | 9.6  | 0.29 | 3.64E-05 | N | Y |
| Case 45 | 0.18 | 0.09 | 0.04  | 8.0 | 4.0 | 9.6  | 2.3 | 9.8  | 0.27 | 4.61E-05 | N | Y |
| Case 46 | 0.20 | 0.09 | 0.04  | 7.8 | 3.9 | 9.5  | 1.7 | 9.5  | 0.25 | 2.13E-05 | N | Y |
| Case 47 | 0.21 | 0.09 | 0.04  | 8.0 | 3.3 | 9.7  | 1.7 | 9.8  | 0.24 | 5.01E-05 | N | Y |

|         |      |      |      |     |     |      |     |      |      |          |   |   |
|---------|------|------|------|-----|-----|------|-----|------|------|----------|---|---|
| Case 48 | 0.22 | 0.09 | 0.04 | 8.0 | 3.3 | 9.8  | 1.7 | 9.8  | 0.23 | 5.77E-05 | N | Y |
| Case 49 | 0.24 | 0.09 | 0.04 | 7.9 | 2.9 | 9.7  | 1.5 | 9.8  | 0.21 | 3.40E-05 | N | Y |
| Case 50 | 0.26 | 0.09 | 0.04 | 7.9 | 2.7 | 9.8  | 1.2 | 9.8  | 0.19 | 3.44E-05 | N | Y |
| Case 51 | 0.28 | 0.09 | 0.04 | 8.0 | 2.2 | 9.9  | 1.0 | 9.8  | 0.17 | 8.33E-05 | N | Y |
| Case 52 | 0.30 | 0.09 | 0.04 | 7.9 | 2.1 | 9.9  | 1.2 | 10.0 | 0.15 | 7.40E-05 | N | Y |
| Case 53 | 0.60 | 0.09 | 0.04 | 8.0 | 1.1 | 10.2 | 1.1 | 10.2 | 0.00 | 1.88E-04 | Y | Y |
| Case 54 | 1.00 | 0.09 | 0.04 | 7.9 | 1.5 | 10.2 | 1.5 | 10.2 | 0.00 | 2.75E-04 | Y | Y |
| Case 55 | 1.40 | 0.09 | 0.04 | 8.0 | 1.8 | 10.6 | 1.8 | 7.8  | 0.00 | 1.86E-04 | Y | Y |
| Case 56 | 0.10 | 0.09 | 0.08 | 8.1 | 5.2 | 9.6  | 2.4 | 9.7  | 0.30 | 2.29E-05 | N | Y |
| Case 57 | 0.16 | 0.09 | 0.08 | 8.1 | 4.1 | 10   | 1.6 | 10.0 | 0.24 | 2.08E-05 | N | Y |
| Case 58 | 0.18 | 0.09 | 0.08 | 8.1 | 3.8 | 10   | 1.5 | 10.1 | 0.22 | 2.87E-05 | N | Y |
| Case 59 | 0.19 | 0.09 | 0.08 | 8.1 | 3.4 | 10.1 | 1.4 | 10.2 | 0.21 | 3.43E-05 | N | Y |
| Case 60 | 0.20 | 0.09 | 0.08 | 7.8 | 3.0 | 9.8  | 1.2 | 9.9  | 0.20 | 4.83E-05 | N | Y |
| Case 61 | 0.21 | 0.09 | 0.08 | 7.9 | 3.0 | 10   | 0.9 | 9.9  | 0.19 | 3.17E-05 | N | Y |
| Case 62 | 0.22 | 0.09 | 0.08 | 7.9 | 1.7 | 9.9  | 0.7 | 10.0 | 0.13 | 5.03E-05 | N | Y |
| Case 63 | 0.24 | 0.09 | 0.08 | 7.9 | 1.4 | 10   | 0.3 | 10.0 | 0.16 | 5.22E-05 | N | Y |
| Case 64 | 0.26 | 0.09 | 0.08 | 8.0 | 1.4 | 10.4 | 0.3 | 10.4 | 0.14 | 4.32E-05 | N | Y |
| Case 65 | 0.28 | 0.09 | 0.08 | 8.0 | 1.2 | 10.5 | 0.2 | 10.4 | 0.12 | 4.78E-05 | N | Y |

---