

Secondary flow structure and sediment deposition around flexible and rigid vegetation patches

Secondary Flow Structure and Sediment Deposition around Flexible and Rigid Vegetation Patches

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Vegetation plays a crucial role in aquatic systems and characterizes riverine ecosystems. To predict changes in riverine environment, it is essential to understand the influences of vegetation on flow structure and sediment transport. The present study explores the effects of deflection of flexible vegetation elements on vortex structure and sediment deposition around a vegetation patch through flume experiments. First, velocity measurement by particle image velocimetry (PIV) was performed for flows around a single upright/inclined rigid strip blade and around a single/three-row patch of the inclined blades to investigate the effect of deflection of vegetation elements on flow structure. Second, the effects of vegetation flexibility on the flow structure and sediment deposition in the vegetation patch wake region were explored by vertical and horizontal PIV measurements and sediment deposition experiments. In this part, we considered three types of vegetation patch models consisting of rectangular blades arranged in a square lattice array: (1) rigid, emergent vegetation; (2) flexible, submerged vegetation; (3) rigid, submerged vegetation. In the flexible vegetation case, a rotating secondary flow is generated by the deflection of vegetation elements and significantly contributes to momentum transport into the vegetation patch wake region, while the turbulent mixing by vertical or horizontal vortices determines the wake region behind the rigid vegetation patches. Moreover, the secondary flow around the flexible vegetation patch increases the spanwise sediment transport fluxes across the lateral patch edges and thereby enhances the sediment deposition behind the vegetation patch.

1. INTRODUCTION

Vegetation plays a crucial role in aquatic ecosystems by providing habitats for various organisms. In natural rivers, aquatic vegetation closely interacts with mass and momentum transport processes and bed morphology to create complexity and diversity of riverine landscape (Caroppi and Järvelä, 2022; Larsen, 2019; Nikora et al., 2008). For example, a small-scale vegetation patch in a river channel reduces surrounding flow velocity and thereby promotes sediment deposition, resulting in evolution of the vegetation patch into a large-scale vegetated area over an entire river channel (Yamasaki et al., 2019). Therefore, for precise prediction of changes in riverine environment, it is essential to understand the influence of vegetation patches on flow structure and sediment transport processes.

Many researchers have focused on turbulence structure in aquatic canopy flow to reveal the mass and momentum transport mechanisms. Over aquatic vegetation, the mixing layer develops near vegetation tips because of the large velocity difference between the regions within and over a vegetation canopy. This leads to generation of large-scale

vertical vortices rotating about the spanwise axis in a vertical plane due to the Kelvin-Helmholtz (K-H) instability (Ghisalberti and Nepf, 2002; Poggi et al., 2004). Some researchers have explored the spatial evolution of the mixing layer from the leading patch edge (Okamoto and Nezu, 2013; Sukhodolov and Sukhodolova, 2012). Similarly, in partially vegetated open-channel flow, the velocity difference across the lateral patch edge generates the horizontal vortices that rotate about the vertical axis in a horizontal plane (Caroppi et al., 2021; Liu et al., 2024). Rominger and Nepf (2011) investigated the flow adjustment process at the leading edge of an emergent, rectangular vegetation patch. They evaluated the interior adjustment length where the streamwise flow velocity is reduced and the development process of the mixing layers around the lateral vegetation edges. Moreover, around a submerged vegetation patch, vertical and horizontal vortices are generated around the top and lateral patch edges, respectively (Nezu and Onitsuka, 2001; Unigarro Villota et al., 2023; Yan et al., 2022).

Since vegetation can exhibit a range of biomechanical properties, from rigid to highly flexible, the flexibility of vegetation elements is an important parameter to characterize the vegetation-canopy flow. For flexible vegetation flow,

1 coherent structures of turbulence cause the waving motions
2 of plants called 'monami' for aquatic canopies (Ghisalberti
3 and Nepf, 2006). Conversely, the deflection and waving mo-
4 tion of vegetation elements also affect the flow structure
5 within and over a vegetation layer. Regarding the mean and
6 turbulent flow structure, there are significant differences be-
7 tween rigid and flexible vegetation flows (Albayrak et al.,
8 2012; Nepf, 2012; Hu et al., 2018). Marjoribanks et al.
9 (2017) compared the temporal scale of vortex for semi-rigid
10 canopy flow with that for highly flexible canopy flow, and
11 indicated that over the highly flexible vegetation, waving
12 vegetation elements might induce a small-scale turbulence
13 structure in addition to the large-scale coherent structure.
14 Houseago et al. (2022) pointed out the barrier effect of plant
15 deflection may prevent the large-scale turbulence transport
16 from penetrating into a vegetation layer. The transformation
17 of flow structure by plant deflection has motivated many
18 studies to investigate how aquatic plants respond to the tur-
19 bulent motion of fluid (Boothroyd et al., 2017; Sinicalchi
20 and Nikora, 2013). Okamoto et al. (2016) measured the veg-
21 etation tip motion and surrounding flow velocity simultane-
22 ously by particle image velocimetry (PIV) and particle track-
23 ing velocimetry (PTV). Their results revealed the number of
24 vegetation elements deflected at the same time depends on
25 the length-scale of the vortex in the mixing layer. A numeri-
26 cal simulation by Tschisgale et al. (2021) revealed momen-
27 tum exchange is enhanced by the K-H vortex below a high-
28 speed region and the hairpin vortex around a low-speed
29 streak. Wang et al. (2022) observed that the 'monami' is in-
30 duced by a pair of counter-rotating spanwise vortices passing
31 over the vegetation height and streamwise scale of the co-
32 herent structure determines the wavelength of the waving
33 motion of vegetation elements. These examinations all re-
34 confirm the importance of flexural rigidity of plants in mass
35 and momentum transport processes within and over a vege-
36 tation patch.

37 Many researchers have also investigated the effects of
38 turbulence on sediment transport behind a vegetation patch
39 (Das et al., 2023; Huai et al., 2021; Liu et al., 2021; Ortiz et
40 al., 2013; Västilä and Järvelä, 2018; Yager and Schmeeckle,
41 2013; Zhang et al., 2024). Zong and Nepf (2012) examined
42 the flow structure behind a rigid, emergent vegetation patch
43 by acoustic Doppler velocimetry (ADV) and flow visualiza-
44 tion. They proposed a simplified prediction model for the
45 wake-length L_{HV} assuming linear growth of the horizontal
46 mixing layer around the lateral patch edge as follows:

$$47 \quad L_{HV} = b_p \frac{\bar{U}}{S_\delta \Delta U} \quad (1)$$

48 where b_p is the half-width of a vegetation patch, $\bar{U}$ is the
49 average of the streamwise velocities inside and outside a
50 patch wake, ΔU is the velocity difference across the shear
51 layer, and S_δ is the growth rate of the shear layer. In the
52 same way, the wake-length behind a submerged vegetation

53 patch L_{VV} can be estimated based on the assumption that
54 the vertical mixing layer develops around the vegetation
55 height. Liu et al. (2018) suggested that a deposition area
56 downstream of a patch is determined by whether vertical or
57 horizontal vortices first reach the channel bed at the patch
58 centerline. Marjoribanks et al. (2019) investigated effects of
59 vegetation flexibility on the patch-wake flow and demon-
60 strated that the flexural rigidity is an important factor to de-
61 termine the vortex development and sediment deposition
62 area. They also modified Eq. (1) to incorporate the effects of
63 deflection of flexible vegetation elements as follows:

$$64 \quad L_{VV} = x_d + h_d \frac{\bar{U}}{S_\delta \Delta U} \quad (2)$$

65 where (x_d, h_d) is the tip position of a deflected vegetation
66 element at the downstream patch end. These studies have
67 provided valuable knowledge to estimate the velocity distri-
68 bution and fine sediment deposition in the patch-wake re-
69 gion. However, the simplified models [Eqs. (1) and (2)] do
70 not fully account for the three-dimensional structure of mean
71 (secondary flow) and turbulent flows (vertical and horizontal
72 vortices) around a vegetation patch. Moreover, few studies
73 have revealed the difference in the secondary flow structure
74 between rigid and flexible vegetation patches, although it de-
75 termines the mass and momentum transports and the sedi-
76 ment deposition in the patch-wake region.

77 The purpose of this study is to investigate the effects of
78 deflection of flexible vegetation elements on the flow struc-
79 ture and sediment deposition around a vegetation patch
80 through flume experiments. First, to focus on the effect of
81 deflection of vegetation elements on flow structure, velocity
82 measurements by PIV are performed for flows around up-
83 right and inclined single rigid strip blades and around single-
84 and three-row patches of the inclined rigid blades. Having
85 established the impact of stem inclination on flow structure,
86 the effects of vegetation flexibility on the flow structure and
87 sediment deposition around a wide vegetation patch are ex-
88 plored by vertical and horizontal PIV measurements and sedi-
89 ment deposition experiments. In the velocity measurements,
90 the three-dimensional velocity distributions are obtained by
91 shifting measurement plane positions in the spanwise or ver-
92 tical directions to reveal the secondary flow structure around
93 a vegetation patch. In the deposition experiments, sediment
94 deposition in the vegetation patch wake region is observed
95 by introducing fine sediment particles into the flow field and
96 measuring the streamwise distribution of the sediment dep-
97 osition by weight. In this part, we consider three types of
98 vegetation patch models consisting of rectangular blades ar-
99 ranged in a square lattice array: (1) rigid, emergent vegeta-
100 tion; (2) flexible, submerged vegetation; (3) rigid, sub-
101 merged vegetation. Comparison between the first and second
102 cases with the same non-deflected vegetation height sheds
103 light on the effects of the deflected height of vegetation ele-
104 ments on the vortex and secondary flow structure. In

1 addition, the vegetation height for the rigid, submerged case
2 is set at the value equivalent to the deflected height of the
3 flexible vegetation elements, which aims to reveal the de-
4 pendence of momentum and sediment transport, especially
5 of the secondary flow structure, on the bending shape and
6 flexibility of the vegetation elements.

7 II. EXPERIMENTAL METHODS

8 A. Velocity measurement for flows around inclined 9 blade elements

10 1. Experimental setup and hydraulic conditions

11 Experiments were performed in a 10 m long, $B = 0.40$
12 m wide, 0.50 m high glass flume. Water was pumped up
13 from a water tank at the downstream end to the flume inlet
14 and circulated in the enclosed system. The x -, y - and z -
15 axes correspond to the streamwise, vertical and spanwise co-
16 ordinates, respectively, and the coordinate origin is located
17 4 m downstream of the flume inlet ($x = 0$), at the channel
18 bottom ($y = 0$), and at the channel centerline ($z = 0$). The
19 corresponding components of instantaneous flow velocity
20 ($\tilde{u}, \tilde{v}, \tilde{w}$) are decomposed into the time-averaged compo-
21 nents (U, V, W) and instantaneous fluctuating components
22 (u, v, w), i.e., $\tilde{u} \equiv U + u$, $\tilde{v} \equiv V + v$ and $\tilde{w} \equiv W + w$.

23 Velocity measurement was performed for two types of
24 flow fields as shown in Fig. 1. First, we considered the flow
25 fields around a single vegetation element: upright (Case A1)
26 and inclined (A2) ones [Fig. 1(a)] to explore how the incli-
27 nation of a strip blade changes flow structure around an in-
28 dividual strip element. As rigid vegetation elements, we used
29 acrylic strip blades of a width of $b = 0.8$ cm, and a thick-
30 ness of $t_v = 0.2$ cm. The flexural rigidity of the rigid vege-
31 tation element was estimated at $EI = 1.8 \times 10^{-2} \text{ Nm}^2$, where
32 E and I are the bending elastic modulus ($E = 3.4 \times 10^9$
33 Nm^2 for acrylic resin) and the second moment of area ($I =$
34 $bt_v^3/12$), respectively. In the upright element case, the rigid
35 blade with a length of $h = 7.0$ cm was attached perpendic-
36 ular to the channel bed. On the other hand, the acrylic blade
37 of a length of $h = 14.0$ cm was tilted 60° in the streamwise
38 direction in the inclined element case (tilting angle $\theta =$
39 60°). The vegetation height, that is, the distance between the
40 vegetation tip and the channel bed, was $h_v = 7.0$ cm in both
41 cases. The other flow field is the flows around single- (Case
42 B1) and three-row (B2) vegetation patches consisting of the
43 inclined strip elements. The shape and tilting angle of each
44 vegetation element model was the same as the inclined sin-
45 gle element case. The vegetation patch was constructed
46 along the channel centerline by aligning 12 vegetation ele-
47 ments at intervals of $L_v = 3.2$ cm, and the streamwise patch
48 length L_p was 0.352 cm. For the three-row patch, the
49 spanwise interval of the strip elements was $B_v = 3.2$ cm,
50 and the patch centerline was set along the flume centerline

51 ($z = 0$). By comparing the single- and three-row patch cases,
52 the influence of the number of vegetation elements on flow
53 structure will be discussed. The bulk mean velocity $U_m \equiv$
54 Q/BH (Q is the flow discharge) was 0.25 m/s for all flow
55 conditions. The water depth was adjusted at $H = 0.150$ m
56 and kept uniform throughout the measurement area by a weir
57 at the downstream flume end.

58 2. PIV measurement

59 The two-component data of instantaneous flow velocity
60 in xy -planes ($\tilde{u}, \tilde{v}$) was obtained by PIV. The test areas
61 were $-0.5 \leq x/H \leq 1.5$ for the single vegetation element
62 and $-0.5 \leq x/H \leq 4.5$ for the single- and three-row vege-
63 tation patches. A laser light was generated by a 3.0 W YAG
64 laser source and converted into a 2.0 mm-thick laser light
65 sheet (LLS) by a cylindrical lens. The LLS was projected
66 vertically through the water surface. The spanwise positions
67 of LLSs were $z = 0$ (the vegetation element centerline)
68 and $z = b$ (the side of the vegetation element) for the single
69 upright/inclined vegetation element; $z = 0$ (the patch cen-
70 terline) and $z = 4b$ (the patch side) for the single-row
71 patch; $z = 0$ (the patch centerline), $z = 2b$ (between veg-
72 etation elements) and $z = 8b$ (the patch side) for the three-
73 row patch [Fig. 1(b)]. Here, the laser light passed through
74 the vegetation element without significant reflection, refrac-
75 tion or dispersion because the acrylic vegetation elements
76 were transparent and thin. As fluid tracers, Nylon-12 parti-
77 cles with a diameter of 100 μm and a specific gravity of 1.02
78 were added to the water. The seeding particle density in the
79 water was approximately $9.5 \times 10^7 \text{ m}^{-3}$. The flow images vis-
80 ualized by the illuminated tracers were recorded using a
81 high-speed camera (HAS-EF, Ditect) controlled by a per-
82 sonal computer and connected to a pulse signal generator.
83 The resolution of the recorded images was 1280×1024 pix-
84 els (approximately 20 cm $\times$ 15 cm in real scale), and the
85 frame rate of the camera was 500 Hz. The data sampling rate
86 was 30 Hz: the pulse signal generator extracted and recorded
87 a pair of images every 1/30 s (Matsumoto et al., 2024; Oka-
88 moto and Nezu, 2013; Okamoto et al., 2016). The number of
89 sampled image pairs was 1800 and the total sampling time
90 was 60 s for each measurement. The test area was divided
91 into 2 fields of view (FOVs) for the single strip blade flows
92 and 4 FOVs for the patch flows, and the velocity measure-
93 ment was conducted for each FOV.

94 From the recorded images, velocity data were calculated
95 based on the direct cross-correlation method. The size of in-
96 terrogation windows was 19×19 pixels (about 0.38 cm $\times$
97 0.38 cm), and flow velocity calculation points were spaced
98 at 0.33 cm intervals. Although the overlap of the interroga-
99 tion windows was only 14%, the measurement grid for PIV
100 was spatially resolved enough to capture large-scale flow
101 structures around the vegetation elements. To remove error
102 vectors from the raw vector data, velocity data at points
103 where the correlation coefficient between the brightness

distributions of a pair of interrogation windows is very small (less than 0.5) were removed and interpolated with the median of velocity data at neighboring points at each time.

B. Velocity measurement and deposition experiment for a wide vegetation patch

1. Experimental setup and hydraulic conditions

Figures 2(a) and 2(b) show schematic views of the experimental setup and the coordinate system for the flows around wide vegetation patches. The experiments in this part were performed in the same glass flume as the velocity measurement described in the previous section. A rectangular vegetation patch was constructed around the channel centerline. The patch width was $2b_p = 0.136$ m (b_p is the half-width of a vegetation patch) and the ratio of the patch width to the channel width was $2b_p/B = 0.34$, which ensures that effects of the channel side walls were negligible (Liu et al., 2018; Marjoribanks et al., 2019; Ortiz et al., 2013; Zong and Nepf, 2012). Rigid and flexible rectangular blades were attached to the channel bed in a square pattern as vegetation elements [Fig. 2(a)]. The rigid vegetation element models were acrylic blades ($h = 7.0$ cm or 15.0 cm; $b = 0.8$ cm; $t_v = 0.2$ cm; $EI = 1.8 \times 10^{-2}$ Nm²) [Nezu and Sanjou, 2008; Okamoto and Nezu, 2013]. On the other hand, rectangular polytetrafluoroethylene (PTFE) sheets were used as flexible vegetation elements ($h = 15$ cm; $b = 0.8$ cm; $t_v = 0.04$ cm; $E = 5.5 \times 10^8$ Nm²; $EI = 2.3 \times 10^{-5}$ Nm²). Since the flexible vegetation elements were not transparent and were longer and thicker than those in Okamoto and Nezu (2009), the flow field near the vegetation height was obscured by the deflected vegetation elements in the PIV measurement. The ratio of the vegetation height to the patch width was $h/(2b_p) = 0.5$ – 1.1 , which is in the range of values observed in field data by Marjoribanks et al., 2019. The streamwise and spanwise intervals of vegetation elements (L_v and B_v , respectively) were constant in all cases ($L_v = B_v = 3.2$ cm).

Table I shows the experimental conditions in the present study. The velocity measurements and the deposition experiments were conducted for three flow scenarios: emergent, rigid vegetation flow (R1, $h_v/H = 1$); submerged, flexible vegetation flow (F, $h_v/H = 0.53$); submerged, rigid vegetation flow (R2, $h_v/H = 0.47$) [Fig. 2(d)]. The non-deflected vegetation heights h for Cases R1 and F were the same ($h = 15$ cm), but Case F was the submerged vegetation flow due to the deflection of flexible vegetation elements. Comparison between Cases F and R2 focuses on effects of the bending shape of vegetation elements because the deflected heights in Case F were comparable to that in Case R2 ($h_v \approx 0.5H$). The submergence depth ratios for the submerged vegetation cases were approximately $H/h_v \approx 2$, where the vertical mixing layer is most efficiently generated around vegetation tips (Martino et al., 2012; Matsumoto et

al., 2023). The patch blockage ratios, defined as $2b_p h_v / (BH)$, for Case R1, F, and R2 were 0.34, 0.18, and 0.16, respectively.

The solid volume fraction of the vegetation patch, $\phi \equiv (bt_v h) / (L_v B_v h_v)$, was $\phi = 0.016$ for the rigid vegetation cases (R1 and R2) and $\phi = 0.006$ for the flexible vegetation case (F). The vegetation density was $a = 7.8$ m⁻¹ for all cases, and was defined as the total frontal area of vegetation elements divided by the canopy volume as follows (Okamoto and Nezu, 2013):

$$a = \frac{n_v h_v b}{h_v A_b} = \frac{n_v b}{A_b} \quad (3)$$

where A_b is the reference bed area, and n_v is the number of vegetation elements within a vegetation patch ($n_v = 5 \times 24$). Both ϕ and a were within the range of the field data for marsh grass reported by Nepf (2012).

This study focuses on the effects of the flexibility of vegetation elements on flow structure and sediment deposition pattern. Therefore, the bulk mean velocity U_m , the flow depth H , and the vegetation density a were kept constant among all cases ($U_m = 0.25$ m/s). Reynolds number and Froude number are defined with the bulk mean velocity and flow depth, i.e., $Re \equiv U_m H / \nu$ and $Fr \equiv U_m / (gH)^{0.5}$ where g and ν denote the gravitational acceleration and the kinematic viscosity of water, respectively. In addition, the Cauchy number Ca is an important parameter to qualitatively estimate the vegetation motion type (Luhar and Nepf, 2016; Marjoribanks et al., 2019; Tschisgale et al., 2021), and is defined as the ratio of drag force to flexural rigidity of vegetation elements:

$$Ca = \frac{\frac{1}{2} \rho b h U_m^2}{EI/h^2} = \frac{\rho b U_m^2 h^3}{2EI} \quad (4)$$

For Cases R1 and R2, the Cauchy numbers were $Ca = 4.6 \times 10^{-2}$ and 4.7×10^{-3} , respectively, indicating the oscillation of vegetation elements was negligible ($Ca \ll 1$). Contrary, the amplitude of waving motion of vegetation elements is significantly large in Case F since $Ca = 36$ ($Ca \gg 1$).

2. PIV measurement

The two-component data of instantaneous velocity in xy -plane ($\tilde{u}, \tilde{v}$) and in xz -plane ($\tilde{u}, \tilde{w}$) were obtained by vertical [Fig. 2(a)] and horizontal PIV [Fig. 2(b)], respectively. The test area for the velocity measurements started from about 3.7 m downstream of the flume inlet (-0.30 m $< x < 1.35$ m), where the flow was fully developed. For validation, the velocity measurement was also performed at the channel centerline ($z = 0$) 4 m downstream of the flume inlet for the smooth bed flow (without any vegetation elements or patches). The LLS generated by a 3.0 W YAG laser source was projected vertically through the water surface in vertical PIV and horizontally through the glass-made sidewall in horizontal PIV. The other detailed setups for PIV were the same

as the velocity measurements for the single vegetation element and the single-row vegetation patch.

For the flexible vegetation case (Case F), the tip motions of flexible vegetation elements were analyzed using a PTV technique (Okamoto and Nezu, 2009; Okamoto et al., 2016). The fluorescence markers (Nylon-12 particles with a diameter of 1.0 mm and a specific density of 1.02) were attached on the corner edges of the vegetation elements located at the centerline of the channel ($z = 0$). Then, the LLS was projected onto the markers from the free surface, and motions of the markers were recorded using the high-speed camera in the same way as the vertical PIV measurement. Using the PTV technique, the time-series data of the tip positions, $(x_d(t), h_d(t))$, were successfully obtained.

The velocity measurement in this section consists of three parts. Firstly, the vertical PIV measurement was performed for the entire test area ($-2 < x/H < 9$). The test area was divided into 12 FOVs with a streamwise length of about 0.15 m, and the velocity measurement was repeatedly performed to cover the entire test area. The spanwise position of the LLS was near the centerline of a vegetation patch ($z/b_p = 0.24$). Secondly, horizontal PIV measurement was also performed for the same area as the vertical PIV measurement. The vertical positions in horizontal PIV were at $y/H = 0.07$ (near the channel bed) and $y/H = 0.33$ (near the vegetation tips for Cases F and R2). Finally, the vertical and horizontal PIV measurements were repeatedly performed for the vegetation patch wake region ($x/H \approx 6$ and 8) while shifting the spanwise and vertical positions of the LLS to reveal the three-dimensional distributions of flow velocity. The measurement area covered a region within and around the vegetation patch and its wake region ($0 \leq y/H \leq 0.6$; $0 \leq z/b_p \leq 1.6$), and the vertical and spanwise intervals of the LLS positions were $\Delta y = 1$ cm ($= 0.07H$) and $\Delta z = 1.6$ cm ($= 0.5b_p$), respectively. Grid-point data of time-averaged velocities (U, V, W) and turbulence statistics ($-\overline{uv}$ and $-\overline{uw}$) in a cross-sectional (yz -) plane were obtained by combining datasets of the vertical and horizontal velocity measurements, and then the values between grid points were calculated by bilinear interpolation.

3. Sediment deposition experiments

The flow structure within and around a vegetation patch strongly affects sediment transport rate and deposition areas. Fine sediment deposition is likely enhanced in the vegetation patch wake region where the time-averaged flow velocity and turbulence intensity is small enough not to disturb fine sediment particles on the riverbed. In this point, we should further investigate how the vortex structure and secondary flows influence momentum and sediment transport processes in a vegetation patch wake region. Ortiz et al. (2013) measured the streamwise distribution of sediment deposition weight per unit area for cylindrical canopy flows. The present study employed a similar approach for the rigid and

flexible canopy flows to investigate how the flow structure influences the amount and spatial distribution of fine sediment deposition around a vegetation patch. Figure 2(c) presents an overview of the sediment deposition experiments. Silica sand with a mean diameter of $d = 105 \mu\text{m}$ and a specific gravity of $\sigma/\rho = 2.65$ was adopted as sediment particles. The settling velocity was estimated at $V_t = 0.92$ cm/s by Rubey's equation (Rubey, 1933):

$$\frac{V_t}{\sqrt{sgd}} = \sqrt{\frac{2}{3} + \frac{36v^2}{sgd^3}} - \sqrt{\frac{36v^2}{sgd^3}} \quad (5)$$

where s is the specific gravity in water ($= \sigma/\rho - 1$). The critical shear velocity was $u_{*c} = 1.32$ cm/s (Iwagaki, 1956). Shi et al. (2016) reported that a vegetation patch creates significant spatial variation in sediment deposition areas only when the ratio of the flow friction velocity to the critical shear velocity u_*/u_{*c} is within the range of $0.7 < u_*/u_{*c} < 3$. The ratio for the present particles was $u_*/u_{*c} = 0.9$ ($u_* = 1.2$ cm/s), suggesting the adequacy of the selected sediment particles for the experimental purpose.

The sand particles were added to the working water with a volume/volume concentration of 9.4×10^{-4} . Two drainage pumps (LSC-1.4S, Tsurumi Pump) were installed in the downstream water tank to agitate the sediment particles and water sufficiently, preventing sediment accumulation inside the tank and reduction in the sediment concentration during experiments. Square slide glasses ($22 \text{ mm} \times 22 \text{ mm}$) were arranged on the channel bed in the wake region ($5 < x/H < 9$) along the channel centerline ($z = 0$) with interval $\Delta x = L_v = 3.2$ cm. The sediment-laden water was recirculated for two hours in each measurement, which is long enough to stabilize the state of sediment deposition. It was observed in preliminary experiments that the states of sediment deposition were almost the same 2 and 4 hours after the start of water circulation. After the water recirculation, flow discharge was slowly reduced to zero and the slide glasses were removed from the flume carefully in order not to disturb sediment samples on the plates. The set of slide glasses were fully dried for more than two days, and then the weight of each sample was measured by a digital scale with a minimal scale of 0.001 g. To ensure reproducibility and to evaluate uncertainty of results, the measurements were replicated three times for each case, and the results of the sediment deposition weight presented in this paper are the average values among the repeated measurements. The standard deviations of the total deposition weight over the test section ($5 < x/H < 9$) across three measurement runs were 0.4%, 4.8% and 1.3% of the average values for Cases R1, F and R2, respectively.

III. Results

1 A. Validation of the smooth bed flow

2 The velocity data for the smooth bed flow is analyzed to
3 validate the flow development around the test area. Figures
4 3(a) and 3(b) show the velocity profile: (a) the plot of U/U_m
5 versus y/H and (b) the semi-log plot of $U^+ \equiv U/u_*$ ver-
6 sus $y^+ \equiv yu_*/\nu$. Here, u_* is the flow friction velocity and
7 was estimated at $u_* = 0.012$ m/s by fitting the velocity pro-
8 file measured over the smooth bed to the log-law distribution
9 [shown in Fig. 3(b) as a dashed line]:

$$10 \quad U^+ = \frac{1}{\kappa} \ln y^+ + C_{\log} \quad (6)$$

11 where κ is the von Karman's constant and $C_{\log}$ is a con-
12 stant ($\kappa = 0.41$ and $C_{\log} = 5.1$ for open-channel flow).
13 Figure 3(b) demonstrates that the velocity profile is in good
14 agreement with the log-law distribution within $y/H < 0.2$.
15 The flow velocity monotonically increases in the vertical di-
16 rection and has a maximum value at the free surface (the
17 maximum velocity $U_\infty/U_m = 1.18$), suggesting that the
18 boundary layer thickness is equivalent to the flow depth. De-
19 fined as the vertical position δ where $U(\delta) = 0.99U_\infty$, the
20 boundary layer thickness was $\delta/H = 0.88$.

21 The vertical distributions of the streamwise and vertical
22 turbulence intensities (u' and v') are shown in Fig. 3(c).
23 Here, the following scaling equations of the turbulence in-
24 tensities by Nezu and Rodi (1986) are also presented as
25 dashed lines:

$$26 \quad \frac{u'}{u_*} = 2.3 \exp\left(-\frac{y}{H}\right) \quad (7a)$$

$$27 \quad \frac{v'}{u_*} = 1.27 \exp\left(-\frac{y}{H}\right) \quad (7b)$$

28 Moreover, Figures 3 (d–f) present the vertical distributions
29 of the (d) Reynolds shear stress ($-\overline{u'v'}$), (e) skewness ($S_u \equiv$
30 $u'^3/(u')^3$), and (f) flatness ($F_u \equiv u'^4/(u')^4$). For comparison,
31 the values for fully developed open-channel flow by Das et
32 al. (2022) are also shown in the plots. Overall, the turbulence
33 statistics measured in the present study show the same trend
34 as those in the previous studies, demonstrating that the
35 smooth bed flow was well developed around the test area.

36 Figure 4 shows the spanwise distributions of the (a)
37 streamwise and (b) spanwise flow velocities at $y/H = 0.07$
38 and 0.33 ($x = 4$ m). While the streamwise flow velocity U
39 is almost uniform except for the near-wall region, the
40 spanwise flow velocity W varies in the spanwise direction
41 between negative and positive values. This indicates that ro-
42 tating secondary flow cells are generated in the cross-section
43 as illustrated in Fig. 4(c). The pattern of rotating cells is con-
44 sistent with the secondary flow of the second kind by Prandtl
45 for fully developed open-channel flow [Gessner (1973)]. On
46 the other hand, the absolute values of the spanwise flow ve-
47 locity are at most 2% of the bulk-mean velocity U_m .

48 Therefore, considering the uniform distribution of U , the
49 contribution from the secondary flows to momentum
50 transport might be limited.

51 B. Effects of inclination of vegetation elements on 52 flow structure

53 Figure 5 shows the contour maps of the time-averaged
54 streamwise flow velocity U , the vertical flow velocity V ,
55 and the vertical Reynolds shear stress $-\overline{u'v'}$, and the illustra-
56 tions of flow structures for the upright (A1) and inclined
57 (A2) vegetation elements. The flow velocities and length are
58 scaled by the bulk-mean velocity U_m and the blade width
59 b , respectively. Behind the upright vegetation element [Fig.
60 5(a)], the streamwise flow velocity is negative and the ve-
61 locity shear ($\partial U/\partial y$) becomes extremely large around the
62 vegetation height ($y \approx h_v$), indicating the flow separation
63 from the blade surface. The spatial distribution of V
64 demonstrates that upward and downward flows are formed
65 along the vegetation element [Fig. 5(c)]. In contrast, the flow
66 structure around the inclined vegetation element is quite dif-
67 ferent from the upright vegetation element flow [Fig. 5(b)].
68 The vertical flow velocity is positive in front of and behind
69 the inclined element ($V > 0$ in $z = 0$), but negative on the
70 side ($V < 0$ in $z = b$). This means that the flows pushed to
71 the side become downward flows and then become upward
72 flows behind the vegetation element, as illustrated in Fig.
73 5(d). Similar flow structures were reported for flows around
74 an inclined cylinder and attributed to the local pressure gra-
75 dient on the cylinder surface by Choi et al. (2007). As a result,
76 the wake region behind the inclined vegetation element is
77 much smaller than that behind the upright one. The velocity
78 shear $\partial U/\partial y$ and the Reynolds shear stress $-\overline{u'v'}$ behind
79 the upright vegetation tip are much larger than those behind
80 the inclined vegetation tip. Moreover, $-\overline{u'v'}$ is also positive
81 around the side of the inclined vegetation element ($0.1 <$
82 $y/H < 0.5$; $z = b$). This is because the direction of Kar-
83 man vortex shedding is also bent downward by the develop-
84 ment of downward flows (Yeo and Jones, 2008) and it con-
85 tributes to the momentum transport in the vertical direction
86 ($-\overline{u'v'}$).

87 The flow structure around the single-row patch is shown
88 in Figs. 6(a) and 6(b). As well as the flow around the inclined
89 single vegetation element, strong upward flows ($V > 0$) de-
90 velop behind each vegetation element ($z = 0$) [Fig. 6(a)] and
91 downward flows are observed around the vegetation height
92 at the side of the single-row patch ($y \approx h_v$; $z = 4b$) [Fig.
93 6(b)]. Considering the flow continuity, it is likely that fluid
94 is pushed out around the vegetation height ($W > 0$ in $z >$
95 0 ; $W < 0$ in $z < 0$) and flows in near the channel bed
96 ($W < 0$ in $z > 0$; $W > 0$ in $z < 0$) and that there is a
97 pair of flow structures rotating about the streamwise axis.
98 The rotating flows transport the high momentum fluid to the
99 near-bed region and form the negative velocity shear in the
100 vertical direction behind the vegetation patch ($\partial U/\partial y < 0$).

Consequently, the Reynolds shear stress is positive in the mixing layer around the vegetation tips and negative in the negative velocity shear region. Similar features are also observed for the three-row patch flows [Figs. 6(c–e)]. To clarify differences between the two cases, Figure 7 shows the vertical distributions of (a, c) U and (b, d) V downstream of the (a, b) single- and (c, d) three-row patches ($x/H = 3.5$). Overall, the negative velocity shear and the downward flows on the side of the three-row patch are stronger than those for the single-row patch. Therefore, the three-dimensional flow structure around a single inclined element is also observed around a group of the inclined elements, and enhanced as the number of vegetation elements increases.

C. Spatial evolution of flow structure within the wide patch in a vertical plane

Prior to the flow velocity analysis, the vegetation displacement data for the flexible vegetation case (Case F) was examined to reveal the deflected heights and the waving motion of the flexible vegetation elements. Figure 8(a) presents the time-averaged streamwise and vertical positions of deflected vegetation tips ($\bar{x}_d, \bar{h}_d$). Here, the horizontal bars express the maximum and minimum values for each vegetation element. Overall, the deflected heights were approximately half of the flow depth ($\bar{h}_d/H \approx 0.5$) and equivalent to the vegetation height in Case R2 ($h_v/H = 0.47$). In this paper, the average value of deflected vegetation heights among all vegetation elements is used as a representative value of the vegetation height for Case F ($h_v/H = 0.53$). For the vegetation element at the downstream patch end, the time-series of the vertical displacement $\Delta h_d(t)$ and the tip trajectory ($\Delta x_d, \Delta h_d$) are shown in Figs. 8(b) and 8(c), respectively. Here, Δx_d and Δh_d denote the streamwise and vertical displacements from the time-averaged positions, respectively, i.e., $\Delta x_d = x_d - \bar{x}_d$ and $\Delta h_d = h_d - \bar{h}_d$. The amplitude of oscillation was approximately 5% of the flow depth ($0.05H$) and 10% of the time-averaged deflected height ($0.1\bar{h}_d$), indicating the swaying motion of the flexible vegetation elements. In contrast, the vertical amplitudes of the tip positions are very small around the leading patch end and gradually increasing with the streamwise distance from the leading patch end [Fig. 8(a)].

Figure 9(a) shows the contour maps of the time-averaged streamwise flow velocity U for a longitudinal (xy -) plane at $z/b_p = 0.24$ and a cross-sectional (yz -) plane at $x/H = 5.0$. Here, the flow velocity vectors (U, V) are also indicated on the color contours, and the velocity values are normalized by the bulk-mean velocity U_m . The white dashed lines express the outlines of the in-patch region ($0 \leq x \leq L_p$; $0 < y < h_v$). Note that flow velocity data around the vegetation tips was not successfully measured in Case F (light-gray region) because the deflected vegetation elements obscured the FOV. The figures clearly demonstrate that the flow velocity decreases within the vegetation patch

($0 < x/H < 4.9$; $y < h_v$; $z/b_p < 1$) due to drag force. In the rigid, emergent vegetation case (R1), the contour lines of U are almost perpendicular to the channel bed, indicating the formation of vertically uniform flow structure. In contrast, the flow structure in the submerged vegetation cases (F and R2) is not uniform in the vertical direction. The flow velocity above the vegetation height ($y > h_v$) increases and a strong shear layer with positive velocity shear ($\partial U / \partial y > 0$) is generated around the vegetation height. Downstream of the vegetation patch, the streamwise flow velocity increases in the streamwise direction ($\partial U / \partial x > 0$) because the vegetation drag force ceases to affect the flow in this region.

Figure 9(b) shows the contour maps of the time-averaged vertical flow velocity V at $z/b_p = 0.24$ and $x/H = 5.0$. For submerged vegetation (Cases F and R2), upward flow ($V > 0$) is observed near the vegetation tips ($y \approx h_v$), especially near the leading patch end ($x \approx 0$). This upward flow results from the reduction in the streamwise flow velocity ($\partial U / \partial x < 0$) and is called ‘diverging flow’ (Okamoto and Nezu, 2013). This feature is observed in both submerged vegetation cases, but more remarkably in Case R2 because the effect of the vegetation drag force is more significant than that in Case F. In addition, downward flow ($V < 0$) occurs near the channel bed around the leading patch edge ($0 < x/H < 1$; $y/H \approx 0$), which may be generated in the same way as the horseshoe vortex in front of a cylindrical obstruction or vegetation patch (Liu et al., 2021; Unger and Hager, 2007).

The streamwise distributions of U near the channel bed ($y/H = 0.07$; $z/b_p = 0.24$) are shown in Fig. 10(a). The flow velocities are normalized by the approaching flow velocity U_a defined as the near-bed flow velocity far upstream of the vegetation patch ($y/H = 0.07$; $x/H = -2.0$). The reduction in flow velocity within the vegetation patch ($0 < x/H < 4.9$) is slower in the flexible vegetation case (F) than in the rigid vegetation cases (R1 and R2). This suggests the flexibility of vegetation elements decreases flow resistance and relieves the flow adjustment. Comparison between Cases R1 and R2 demonstrates that the flow velocity reduction in the submerged patch is more rapid than that in the emergent vegetation. This is likely because both vertical and spanwise diverging flows develop around the top and lateral edges of the submerged patch (R2), respectively, while only the spanwise one occurs around the emergent patch (R1). Near the downstream patch end ($x/H > 4.6, 3.5$, and 3.9 for Cases R1, F, and R2, respectively), U is almost constant in the streamwise direction, which implies the patch length was long enough to fully reduce the flow velocity within a vegetation patch. The flow velocity remains decreasing or constant in the region just downstream of a vegetation patch ($4.9 < x/H < 5.5$), which is called the ‘steady wake region’ by Zong and Nepf (2012), and starts to increase downstream of this region.

Figures 10(b) and 10(c) show the streamwise

distributions of V near the channel bed for all cases ($y/H = 0.07$; $z/b_p = 0.24$) and near the vegetation height for the submerged vegetation cases ($y = h_v$; $z/b_p = 0.24$), respectively. In Case R2, strong diverging flow ($V > 0$) develops around the leading patch edge ($-1.0 < x/H < 2.0$) and rapidly decays to zero. In contrast, the peak value of the positive vertical velocity in Case F ($V/U_m = 0.04$) is much smaller than that in Case R2 ($V/U_m = 0.16$) but the downward flow persists throughout the vegetation patch ($0 < x/H < 4.9$). The formation of the near-bed downward flow between the flexible vegetation elements can be attributed to the inclination of vegetation elements because the same feature is also observed for the three-row inclined rigid strips [Fig. 6(d)]. These results suggest that the flow adjustment around the leading patch edge becomes more rapid with higher vegetation rigidity. In addition, the near-bed vertical flow velocities are significantly negative over the entire flexible vegetation patch ($0 < x/H < 4.9$ in Case F), while the downward flow is observed only around the leading patch edge ($0 < x/H < 1$) for Cases R1 and R2 [Fig. 10(b)]. The upward flows around the deflected vegetation tips and the remarkable downward flows between the flexible vegetation elements can be attributed to the inclination of the flexible vegetation elements, as demonstrated by Figs. 5(b) and 6.

Figure 11(a) shows the contour maps of the vertical Reynolds shear stress $-\overline{uv}$ for submerged vegetation cases (F and R2). As reported by some previous studies (Nepf, 2012; Okamoto and Nezu, 2013; Tschisgale et al., 2021), the vertical Reynolds stress is significantly positive around the vegetation height in both cases ($-\overline{uv} > 0$). The contour maps for a yz -plane also demonstrate that the development of the vertical mixing layer around the vegetation tips is almost uniform in the spanwise direction over the vegetation patch. Downstream of the flexible, submerged vegetation patch (Case F), the Reynolds stress is negative ($-\overline{uv} < 0$) near the channel bed ($x/H > 5.8$), where the velocity shear is negative as well ($\partial U/\partial y < 0$) [Fig. 9(a)]. In the rigid, submerged vegetation case (Case R2), the vertical mixing layer expands from the channel bed to the free water surface, and the negative Reynolds stress regions are not observed. To compare momentum transport by vertical vortices, Figure 11(b) presents the streamwise distributions of the peak vertical Reynolds stress $-\overline{uv}_{\text{peak}}$ at $z/b_p = 0.24$, which is defined as the maximum value at each streamwise position. Clearly, the development of vertical vortices around the vegetation height for the rigid, submerged vegetation (R2) is much more significant than that for the flexible vegetation (F). In Case R2, the peak Reynolds stress increases over the vegetation patch ($0 < x/H < 4.9$) and decreases in the patch wake region ($x/H > 4.9$).

The velocity profiles $U(y)$ and the vertical distributions of the Reynolds stress $-\overline{uv}(y)$ at $x/H = 1, 3, 5$, and 7 are shown in Figs. 12(a) and 12(b), respectively. In Case R2, the flow velocity is more rapidly reduced within the vegetation

patch ($y < h$) and more rapidly accelerated over the vegetation patch ($y > h$). Consequently, the velocity difference across the vertical shear layer becomes greater and the development of the vertical vortices is more significant than those in Case F. Moreover, the Reynolds stress is positive below the vegetation height near the leading patch edge in Case F ($x/H = 1$; $y < \overline{h_d}$), where the velocity shear $\partial U/\partial y$ is positive but not significantly large. This suggests the momentum exchange by the Karman vortex shedding behind the deflected vegetation elements. Thus, since the deflected vegetation elements cause downward flows and transport a high-momentum flow to the near-bed region, the velocity reduction within the vegetation patch ($y < \overline{h_d}$) becomes slower than that in Case R2 [Fig. 10(a)]. In addition, the flow velocity is significantly accelerated near the channel bed and the velocity shear and Reynolds shear stress become negative ($\partial U/\partial y < 0$; $-\overline{uv} < 0$) only behind the flexible vegetation patch ($x/H = 7$). This also indicates that the momentum transport in the spanwise direction by the three-dimensional flow structure might contribute to the flow reacceleration behind the flexible vegetation patch.

D. Spatial evolution of flow structure within the wide patch in a horizontal plane

The previous section demonstrates that the vertical vortices develop around the vegetation height and their intensity depends on the plant flexibility. This section analyzes the results of the horizontal PIV to investigate the spanwise momentum transport by horizontal vortices and secondary flows. Figures 13(a) and 13(b) show the contour maps of the time-averaged spanwise flow velocity W at $y/H = 0.07$ (near the channel bed) and $y/H = 0.33$ (near the vegetation tips for Cases F and R2). Here, the z -coordinate is normalized by the patch half-width b_p because the flow structure should be symmetrical about the patch centerline ($z = 0$). The light gray strip regions correspond to the unmeasured region where the deflected vegetation elements obscured the FOVs, in the same way as Figs. 9 and 11(a). In the rigid, emergent vegetation case (R1), the spanwise velocity in the non-vegetated side region ($z/b_p > 1$) is positive ($W > 0$) around the leading patch edge ($0 < x/H < 3$) at both elevations, suggesting the flow is diverted from the vegetation patch ($z/b_p < 1$) to the non-vegetated side region ($z/b_p > 1$) due to the vegetation drag. The negative spanwise velocity region appears ($W < 0$) downstream of the patch ($x/H > 4.9$), which indicates that high momentum fluid is transported into the patch wake region and the streamwise velocity increases in the streamwise direction [Fig. 10(a)]. In contrast, the submerged, flexible vegetation patch (F) creates a markedly different flow structure from Case R1. Near the vegetation tips ($y/H = 0.33$), the spanwise diverging flow ($W > 0$) is generated around the lateral patch edge ($z/b_p \approx 1$) from the leading patch edge to the downstream patch edge ($0 < x/H < 4.9$). Conversely, the spanwise flow velocity

1 around the lateral patch edge ($0 < x/H < 4.9$; $z/b_p \approx 1$)
2 is negative ($W < 0$) and the negative W remains in the
3 patch wake region ($x/H > 4.9$) near the channel bed
4 ($y/H = 0.07$).

5 Figures 13(c) and 13(d) show the streamwise distribu-
6 tions of W near the lateral patch edge ($z/b_p = 1.18$) at
7 $y/H = 0.07$ and 0.33 . Comparing Cases R1 and R2, the spa-
8 tial patterns of W are similar and show little variation by
9 the vertical positions. The positive spanwise flow velocity
10 ($W > 0$) around the leading patch edge has the peak value
11 at $x/H = 0$ and decays with distance from the leading
12 patch edge, indicating the formation of the spanwise diverg-
13 ing flow. On the other hand, there is a slight difference in the
14 near-bed flow structure of the patch wake region ($x/H >$
15 4.9 ; $y/H = 0.07$) between Cases R1 and R2. The spanwise
16 flow velocity at $z/b_p = 1.18$ is uniformly negative in Case
17 R1 but increases from negative to positive values in Case R2.
18 This implies that the momentum transport mechanisms into
19 the patch wake region behind the rigid vegetation patch may
20 change due to the vegetation submergence.

21 The contour maps of the horizontal Reynolds shear stress
22 for xz -planes are shown in Figs. 14(a) and 14(b). The values
23 of $-\overline{uw}$ are extremely large in the horizontal mixing layer
24 around the lateral patch edge ($z \approx b_p$), where the velocity
25 shear $\partial U/\partial z$ is extremely large. This demonstrates that the
26 horizontal vortices develop regardless of the submergence
27 depth ratio (H/h_v). However, the horizontal vortices hardly
28 penetrate the lateral patch edge ($z < b_p$) unlike the vertical
29 mixing layer around the vegetation height [Fig. 11(a)]. The
30 horizontal vortices persist behind the vegetation patch
31 ($x/H > 4.9$) and play an important role in the velocity reac-
32 celeration process in the patch wake region ($\partial U/\partial x > 0$) as
33 well as the vertical vortices in the submerged vegetation
34 cases (F and R2).

35 Figures 14(c) and 14(d) present the streamwise distribu-
36 tions of the peak horizontal Reynolds shear stress $-\overline{uw}_{\text{peak}}$
37 at $y/H = 0.07$ and 0.33 , respectively. The horizontal vorti-
38 ces in Case R1 are more significantly generated than those
39 in the other cases. This is because the patch blockage ratio
40 $2b_p h_v/(BH)$ and the velocity shear in the spanwise direc-
41 tion $\partial U/\partial z$ are larger than those in the other cases. The
42 spatial distributions of $-\overline{uw}$ at both elevations ($y/h =$
43 0.07 and 0.33) resemble each other, indicating the weak
44 three-dimensionality in flow structure. Downstream of the
45 vegetation patch ($x/H > 4.9$), the horizontal mixing layer
46 expands in the spanwise direction from the channel center-
47 line ($z = 0$) to the side wall ($z = 0.5B = 2.9b_p$). This sug-
48 gests that the velocity shear in the spanwise direction
49 $\partial U/\partial z$ becomes extremely large around the lateral patch
50 edge because the diverging flow is formed only in the
51 spanwise direction around the emergent vegetation patch. In
52 Case F, the peak Reynolds stress $-\overline{uw}_{\text{peak}}$ at $y/H = 0.07$
53 is larger than that at $y/H = 0.33$, which indicates that the
54 development of horizontal vortices is more remarkable near

55 the channel bed. Moreover, the horizontal vortices with
56 $-\overline{uw} > 0$ are observed to approach the patch centerline
57 ($z = 0$) in $x/H > 4.9$ at $y/H = 0.07$. These features of
58 the horizontal vortices in Case F result from the formation
59 of the secondary flows [Fig. 13]. The secondary flow ($W <$
60 0) transports high momentum into the vegetation patch or
61 the patch wake region ($z < b_p$) near the channel bed. In Case
62 R2, the horizontal mixing layer develops around the lateral
63 patch edge ($0 < x/H < 4.9$; $z \approx b_p$). However, $-\overline{uw}_{\text{peak}}$
64 rapidly decreases behind the patch ($x/H > 4.9$) and the hor-
65 izontal mixing layer does not reach the patch centerline ($z =$
66 0). This is because the momentum exchange by the vertical
67 vortices ($-\overline{uv}$) accelerates the flow velocity in the vegeta-
68 tion patch wake region and thereby more rapidly relieves the
69 velocity shear ($\partial U/\partial z$) than that in the other cases.

70 E. Secondary flow structure behind the wide patch

71 Figure 15 shows the cross-sectional contour maps of (a)
72 the streamwise flow velocity U and (b) the magnitude of
73 secondary flow vectors $\sqrt{V^2 + W^2}$ for all cases (R1, F, and
74 R2). Here, each plot also presents the secondary flow vector
75 distribution (V, W). The streamwise positions of the cross-
76 sections are downstream of the vegetation patch ($x/H = 6.0$
77 and 8.0). For Case F, there is a distinctive flow structure ob-
78 served in the contour maps. The secondary flow vectors in-
79 dicate that a clockwise circulation cell is formed around the
80 lateral patch edge and transports high-speed flow from the
81 non-vegetated side region ($z/b_p > 1$) to the vegetation
82 patch wake region near the channel bed ($y/H < 0.2$;
83 $z/b_p < 1$). The magnitude of secondary flow vectors is
84 largest at $x/H = 6.0$, $y/H \approx 0.13$, and $z/b_p \approx 1$ ($\approx$
85 $0.14U_m$). Consequently, the near-bed flow velocity is accel-
86 erated more rapidly than that around the vegetation tips ($y \approx$
87 $\bar{h}_d$), and $\partial U/\partial y$ becomes negative in this region [Fig. 9(a)].
88 This finding demonstrates the importance of considering the
89 effects of the secondary flows in evaluating the patch wake
90 length behind a flexible vegetation patch. The negative
91 spanwise flow into the vegetation patch wake region is ob-
92 served near the channel bed in Case R1 ($W < 0$; $y/H <$
93 0.4) as well as Case F, but its magnitude is less. Conversely,
94 the rigid, submerged vegetation patch (Case R2) creates a
95 quite different flow structure from the other cases. Down-
96 ward flows ($V < 0$) and negative spanwise flows ($W < 0$)
97 are formed around the vegetation tips ($0.3 < y/H < 0.6$) at
98 $x/H = 6.0$ and develop into a counterclockwise circulation
99 cell ($z/b_p > 0.8$) at $x/H = 8.0$. In addition, the maximum
100 value of $\sqrt{V^2 + W^2}$ for each case is approximately 8–14%
101 of the bulk-mean velocity and much greater than that for the
102 non-vegetated open-channel [Fig. 4(b)], confirming that the
103 observed secondary flow structures are generated mainly by
104 the effect of the vegetation patches.

105 Figures 16(a) and 16(b) show the contour maps of the
106 vertical Reynolds shear stress $-\overline{uv}$ and the horizontal
107 Reynolds shear stress $-\overline{uw}$, respectively. In addition, the

contour maps of the difference between the vertical and horizontal Reynolds stresses $\overline{uw} - \overline{vw}$ are also shown in Fig. 16(c) to compare contributions to momentum transport from the vertical and horizontal vortices (Yan et al., 2022). In Case R1, the horizontal vortices ($-\overline{uw}$) develop most significantly of all cases and penetrate to the patch centerline at any height. The streamwise velocity contour lines in Fig. 15(a) indicate that the flow velocity distribution is almost uniform in the vertical direction [Fig. 9(a)]. These features demonstrate that the horizontal vortices that develop around the lateral patch edge ($z \approx b_p$) mainly characterize the flow structure behind the emergent, rigid vegetation patch. For the flexible vegetation case (Case F), both vertical and horizontal Reynolds stresses ($-\overline{uv}$, $-\overline{uw}$) are smaller than those in the other cases. At the same time, a locally strong horizontal mixing layer ($-\overline{uw} > 0$) develops near the channel bed at $x/H = 6.0$ ($y/H < 0.2$; $0.5 < z/b_p < 1.1$), which results from momentum transport by the clockwise secondary flow. In Case R2, the vertical vortices ($-\overline{uv}$) develop around the vegetation height ($y \approx h$) and the region dominated by the vertical vortices ($-\overline{uv} > -\overline{uw}$) is much larger than that dominated by the horizontal vortices ($-\overline{uv} < -\overline{uw}$). This means that the turbulent mixing by the vertical vortices plays a main role in the momentum transport in and around the rigid, emergent vegetation patch.

F. Sediment deposition behind the wide vegetation patch

The spatial patterns of the sediment deposition behind the vegetation patch ($4.9 < x/H < 9.0$) are presented in Fig. 17(a). The yellow-brown regions in the photographs express the enhanced deposition area, where the black channel bed is covered by silica sand, and the black regions correspond to erosion or no change from the smooth bed flow. In addition, to quantify the spatial patterns of sediment deposition, Figure 17(b) shows the streamwise distributions of the sediment deposition weight per unit area $c(x)$. Here, the plots and the error bars express the mean values and the standard errors among five measurement runs for each case, respectively. When no vegetation models were installed on the experimental flume in a preliminary experiment, little sediment deposition was visually observed and the deposition weight per unit area was $c_0 = 14.6 \pm 1.6 \text{ mg/cm}^2$.

The photographs and the streamwise plots indicate that the sediment deposition pattern seems to reflect the flow structure in the vegetation patch wake region. Behind the rigid, emergent vegetation patch (R1), the enhanced deposition is observed just downstream of the vegetation patch ($4.9 < x/H < 5.5$) and the spanwise width of the deposition area decreases in the streamwise direction. This spatial pattern coincides with the development of horizontal mixing layers [Fig. 14(a)], suggesting the horizontal vortices ($-\overline{uw}$) that develop around the lateral patch edges prevent the stable sediment deposition downstream of the emergent rigid

vegetation patch. The flexible, submerged vegetation case (Case F) has a similar deposition pattern just downstream of the patch ($x/H < 7$), although the horizontal Reynolds shear stress in Case F is much smaller than that in Case R1 [Fig. 14]. This is because the streamlines are deflected around the downstream corners of the vegetation patch by the secondary flow [$W < 0$ shown in Fig. 13(a)], and thereby the horizontal mixing layer approaches the patch wake centerline [Fig. 14(a)]. In addition, the enhanced sediment deposition is also observed far downstream of the patch ($x/H > 7$), where $\partial U/\partial z$ and $-\overline{uw}$ rapidly decrease due to confluence of the secondary flows. Consequently, the total amount of the fine sediment deposition in Case F is larger than those in the rigid vegetation cases.

The rigid, submerged vegetation (R2) enhances the sediment deposition just downstream of the vegetation patch as well as Case R1; however, the spatial pattern is quite different from the other cases. The sediment deposition area in Case R2 is almost constant in width and suddenly disappears at $x/H \approx 5.5$, while the deposition area in Case R1 and F gradually becomes narrower with increasing x -coordinates. The spatial distribution of $-\overline{uv}$ [Fig. 11] shows the vertical vortices penetrate below the vegetation height and reach the channel bed at $x/H \approx 6$, which agrees with the downstream end of the deposition region. Therefore, the vertical vortices play the most significant role in the sediment transport process as well as the momentum transport in Case R2.

IV. DISCUSSION

A. Effects of vegetation deflection on patch resistance

As demonstrated above, the submerged vegetation patches generate different flow structures due to their flexibility. Many studies have focused on the influence of a vegetation patch on mean flow structure to evaluate the flow blockage and resistance by vegetation elements. Specifically, the following blockage parameter Γ_D has been proposed to quantitatively represent the ratio of the patch drag to the advection term in the momentum conservation equation [Chang and Constantinescu (2015); He et al. (2024)]:

$$\Gamma_D = \frac{2C_D a b_p}{1 - \phi} \quad (8)$$

Here, the patch drag coefficient C_D can be estimated by the following model equation [Tanino and Nepf (2008)]:

$$C_D = 2 \left(\frac{\gamma_0}{Re_b} + \gamma_1 \right) \quad (9)$$

where Re_b is Reynolds number defined with the mean flow velocity within a vegetation patch U_{patch} and the

1 vegetation element width b ($Re_b \equiv U_{\text{patch}}b/\nu$); γ_0 and
2 γ_1 are non-dimensional coefficients and dependent on ϕ . In
3 this study, the model coefficients are estimated at $\gamma_0 = 25$
4 and $\gamma_1 = 0.48$ for Case F ($\phi = 0.006$) and at $\gamma_0 = 84$ and
5 $\gamma_1 = 0.52$ for Case R2 ($\phi = 0.016$).

6 The bleed flow velocity right behind the vegetation patch
7 U_e , or the fully reduced in-patch flow velocity, can be esti-
8 mated by the following equation proposed by Rominger and
9 Nepf (2011):

$$10 \quad \frac{U_e}{U_a} = \sqrt{\frac{C_f}{H} \frac{1 - \phi}{C_D a}} \quad (10)$$

11 where C_f is the friction coefficient of the smooth bed ($C_f =$
12 $u_*^2/U_m^2 = 0.002$). Substituting Eq. (8) to Eq. (10), the bleed-
13 ing velocity U_e can be predicted as follows:

$$14 \quad \frac{U_e}{U_a} = \sqrt{\frac{2C_f b_p}{\Gamma_D H}} \quad (11)$$

15 Table II shows the blockage parameters Γ_D and the ra-
16 tios of the bleed flow velocity to the approaching velocity
17 (U_e/U_a) for Cases F and R2. For U_e/U_a , the table compares
18 the measured values in Fig. 10(a) and the predicted values
19 by Eq. (11). Here, the measured values of U_e were esti-
20 mated as the local minimum value behind the vegetation
21 patch ($x/H \approx 6.0$). The measured value of U_e/U_a for Case
22 R2 is of the same order as the predicted one. For Case F,
23 however, there is a great discrepancy between the measured
24 and predicted values and Eq. (11) overestimates the patch
25 resistance. This may be because the model formula of the
26 drag coefficient [Eq. (9)] considers only the influences of the
27 vegetation density and the vegetation element width but ig-
28 nores any detailed geometrical features of the vegetation el-
29 ements. Comparisons between the upright and inclined veg-
30 etation element flows [Fig. 5] indicate that the flow separa-
31 tion region behind a vegetation element diminishes and con-
32 sequently the drag force might decrease as the inclination
33 angle increases. Therefore, the deflection of the flexible veg-
34 etation elements decreases the patch resistance and relieves
35 the velocity difference across the vertical and horizontal
36 mixing layers.

37 B. Formation mechanisms of the secondary flow 38 behind a vegetation patch

39 The results of the velocity measurements demonstrate
40 that secondary flows develop around and behind a vegeta-
41 tion patch and contribute to the momentum transport into the
42 vegetation patch wake region, especially in Case F. Moreo-
43 ver, Figure 15 indicates that two types of secondary flow
44 structures are formed at the right-hand patch edge ($z \approx b_p$),
45 depending on the vegetation flexibility and submergence
46 depth: clockwise rotating cells (Cases R1 and F) and coun-
47 terclockwise cells (Case R2). In each case, the pattern is re-
48 versed at the left-hand patch edge ($z \approx -b_p$). Some previous
49 studies reported the clockwise secondary flow is formed

50 near the channel bed around the lateral patch edge ($y \approx 0$;
51 $z \approx b_p$) and transports high momentum flow to the near-bed
52 region (Yan et al., 2022; Yan et al., 2023). As a result, the
53 near-bed velocity becomes larger than that above. The nega-
54 tive velocity shear ($\partial U/\partial y < 0$) near the lateral patch edge
55 is called 'velocity deflection' and is also observed around the
56 downstream patch end ($x \approx L_p$) for all cases in the present
57 study [Fig. 9(a)]. Many researchers suggest that the second-
58 ary flow is induced by the turbulence anisotropy in a cross-
59 sectional plane (Nezu and Onitsuka, 2001; Yan et al., 2022).
60 Specifically, Yan et al. (2022) pointed out that the region
61 where the horizontal vortices dominate over the vertical vor-
62 tices near the channel bed ($-\overline{uw} > -\overline{wv}$) is consistent with
63 the clockwise circulation cell. This agrees with the result that
64 the clockwise secondary flow was not observed in Case R2,
65 where the vertical vortices reach the near-bed region [Fig.
66 16(a)].

67 The velocity measurements by Yan et al. (2022) also in-
68 dicate that the magnitude of the clockwise circulation cell is
69 enhanced by the turbulence development. However, compar-
70 ing Cases R1 and F in this study, the secondary flow struc-
71 ture is more prominent in Case F, where the horizontal Reyn-
72 olds shear stress $-\overline{uw}$ is much smaller than that in Case R1
73 [Figs. 14 and 16(b)]. Moreover, the negative spanwise flow
74 velocity W near the channel bed ($W < 0$) and the positive
75 W near the vegetation tips ($W > 0$) are observed even
76 around the leading edge of the flexible vegetation patch [Fig.
77 13], where the horizontal mixing layer is not well developed
78 [Fig. 14] and the oscillation of vegetation elements is negli-
79 gible [Fig. 8(a)]. The velocity measurements for the single
80 inclined element [Fig. 5(b)] and the single- and three-row
81 vegetation patches [Fig. 6] also suggest that similar rotating
82 flow cells are generated around inclined (deflected) vegeta-
83 tion elements even if the number of vegetation elements is
84 very small. Therefore, the remarkable secondary flow struc-
85 ture around the flexible vegetation patch (Case F) is derived
86 from the boundary conditions characterized by the bending
87 shape of the flexible vegetation elements, rather than the tur-
88 bulence anisotropy (a mechanism like Prandtl's secondary
89 flow of the second kind). Figure 18 illustrates the formation
90 mechanisms of the secondary flows for all cases. As demon-
91 strated in Figs. 6(b) and 6(e), the streamlines around the in-
92 clined vegetation elements are bent in the spanwise and
93 downward directions ($V < 0$; $W > 0$) around $z \approx b_p$. Sub-
94 sequently, the downward diverging flow reaches the channel
95 bed ($y = 0$) and changes its direction to return to the vege-
96 tation patch ($W < 0$). On the other hand, the oscillation of
97 flexible vegetation elements might also affect the formation
98 of the secondary flow since the vegetation elements around
99 the downstream patch end ($x/H \approx 5$) were visually ob-
100 served to be swaying during the velocity measurements. The
101 velocity profile and the turbulence structure within and over
102 vegetation canopy can change depending on whether the co-
103 herent waving motion of vegetation elements occurs (Nepf,

2012; Marjoribanks et al., 2017). Nevertheless, it is certain that the geometric change in boundary condition by the deflection of flexible vegetation elements contributes to the development of the three-dimensional flow structure around and behind the vegetation patch. The existence of the clockwise secondary flows around the deflected vegetation elements suggests the necessity for simplified models, such as Eqs. (1) and (2), to consider the effect of the bending shape of vegetation elements on secondary flow structure.

As indicated by the spatial distributions of W [Fig. 13], the counterclockwise secondary flow develops only downstream of the rigid, submerged vegetation patch ($x/H > 6$ in Case R2). Similar rotating flow structure was also reported for fully developed turbulent flow over submerged vegetation canopy (Unigarro Villota et al., 2023). Therefore, the counterclockwise rotating secondary flow is likely to be generated over and behind a rigid, submerged vegetation patch if the flow regime is developed to some extent. What makes Case R2 distinctly different from the other cases is the remarkable development of the vertical vortices ($-\bar{w}\bar{v}$) around the vegetation height. In Fig. 17(a), the spanwise flow into the patch wake region ($W < 0$) coincides with the vertical mixing layer ($-\bar{u}\bar{v}$) around the vegetation height ($0.3 < y/H < 0.6$; $z/b_p > 0.7$) at $x/H = 6.0$. This indicates that the development of the vertical vortices determines the flow reacceleration process and causes the counterclockwise secondary flow behind the submerged, rigid vegetation patch. As shown in Fig. 9(a), the streamwise flow velocity increases ($\partial U/\partial x > 0$) due to the vertical turbulent momentum mixing ($-\bar{u}\bar{v}$) around the vegetation height ($y \approx h$). As a result, the downward ($V > 0$) and spanwise flows ($W < 0$ in $z > 0$, or $W > 0$ in $z < 0$) are formed to transport high-momentum flow into the patch wake region ($y < h$; $-b_p < z < b_p$), satisfying the continuity equation ($\partial V/\partial y < 0$; $\partial W/\partial z < 0$). The vertical vortices are developed in Case F as well, but their effects are too weak to counteract the enhanced clockwise secondary flow because $-\bar{u}\bar{v}$ around the vegetation tips is much smaller than that in Case R2.

C. Momentum transfer to the vegetation patch wake region

The flow velocity measurements demonstrate the importance of the vortex structure and secondary flow in the momentum transport around a vegetation patch. Consequently, the flow reacceleration processes in the patch wake region are quite different between the three cases due to the difference in the deflected height and flexibility of vegetation elements. To examine this point, the momentum transfer to the vegetation patch wake region ($x > L_p$; $0 \leq y \leq h_v$; $0 \leq z \leq b_p$) is discussed in this section. The conservation equation of streamwise momentum for steady flow is expressed as follows:

$$\frac{\partial UU}{\partial x} + \frac{\partial UV}{\partial y} + \frac{\partial UW}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + gS_x + \nu \nabla^2 U + \frac{\partial(-\bar{u}\bar{u})}{\partial x} + \frac{\partial(-\bar{u}\bar{v})}{\partial y} + \frac{\partial(-\bar{u}\bar{w})}{\partial z} \quad (12)$$

where P is the time-averaged pressure and S_x is the channel bed slope in the streamwise direction. By integrating Eq. (12) for a cross-section of the patch wake region ($0 \leq y \leq h_v$; $0 \leq z \leq b_p$), the following momentum balance equation can be derived:

$$\frac{\partial(\rho UU)}{\partial x} = \xi - \frac{\tau_b}{h_v} + \frac{\partial(-\rho \bar{u}\bar{u})}{\partial x} + \frac{T_y}{h_v} + \frac{T_z}{b_p} \quad (13)$$

where ξ is the pressure term ($= \rho g(S_x - \partial H/\partial x)$) and τ_b is the channel-bottom shear stress. The angle bracket denotes the cross-sectional averaging operation for the vegetation patch wake region, for example:

$$\langle \rho UU \rangle = \frac{1}{h_v b_p} \int_0^{b_p} \int_0^{h_v} \rho UU dy dz \quad (14)$$

The terms of T_y and T_z are the vertical momentum transfer across $y = h_v$ and the spanwise momentum transfer across $z = b_p$, respectively, and are expressed as follows:

$$T_y = \frac{\rho}{b_p} \int_0^{b_p} \{(-UV)|_{y=h_v} + (-\bar{u}\bar{v})|_{y=h_v}\} dz \quad (15a)$$

$$T_z = \frac{\rho}{h_v} \int_0^{h_v} \{(-UW)|_{z=b_p} + (-\bar{u}\bar{w})|_{z=b_p}\} dy \quad (15b)$$

The vertical and spanwise momentum transfers can be decomposed into the effects of advection (AD) and turbulent mixing (TM) [Dupuis et al. (2024); Vermaas et al. (2011)]. As shown in the Results section, the vertical and horizontal vortices and the secondary flow structure develop around the vegetation patch. Many previous studies attributed the flow reacceleration in the vegetation patch wake region mainly to development of the vertical and horizontal vortices (Liu et al., 2018; Marjoribanks et al., 2019; Zhang et al., 2024; Zong and Nepf, 2012). These terms would play a much more important role in the flow re-acceleration process in the vegetation patch wake region than the other terms in the right hand of Eq. (13). Thus, it is important to reveal the distributions of the vertical and spanwise flow velocities ($-UV$ and $-UW$) and the Reynolds shear stresses ($-\bar{u}\bar{v}$ and $-\bar{u}\bar{w}$) at the vegetation height and the lateral patch edge in understanding the mass and momentum transfer processes into the vegetation patch wake region.

Figure 19(a) shows the vertical distributions of the momentum transports in the spanwise direction across $z = b_p$ ($-UW$ and $-\bar{u}\bar{w}$). As shown in Figs. 15 and 16, the mean flow and turbulence structures are almost uniform in the vertical direction and can be regarded as two-dimensional in Case R1. Therefore, the wake region behind the rigid,

1 emergent vegetation patch is characterized by the vertically
2 uniform development of the horizontal vortices ($-\overline{uw}$),
3 which agrees with the previous investigations of emergent
4 vegetation patch flows (e.g., Zong and Nepf, 2012). Contrary,
5 the spanwise transfer by advection ($-UW$) near the channel
6 bed in Case F is much greater than that in Case R1 although
7 the contribution from turbulent mixing ($-\overline{uw}$) is much
8 smaller. This means that the flow reacceleration downstream
9 of the flexible vegetation patch results from the momentum
10 advection by the secondary flow rather than the horizontal
11 vortices. Figure 19(b) presents the streamwise distributions
12 of the spanwise momentum transfers by advection and tur-
13 bulent mixing, which are defined as the first and second
14 terms in Eq. (15b), respectively. Here, the values of T_z/b_p
15 are normalized by $\rho U_m^2/H$. Overall, the contributions from
16 AD and TM are large in Case R1 but small in Case R2. This
17 is because horizontal vortices develop and contribute to mo-
18 mentum transport more remarkably in Case R1. However,
19 the AD contribution in Case F is much larger than that in
20 Case R2 and as large as the AD and TM contributions in
21 Case R1, although there is little difference in the TM contri-
22 butions between Cases F and R2. This demonstrates that the
23 secondary flows observed in Fig. 15 dominate momentum
24 transfer to the wake region of the flexible vegetation patch
25 instead of horizontal vortices.

26 Figure 19(c) shows the spanwise distributions of the mo-
27 mentum transports in the vertical direction across $y = h_v$
28 ($-UW$ and $-\overline{uw}$). The data for the emergent vegetation
29 (Case R1) is not shown because there is no momentum trans-
30 fer across the vegetation height. The vertical mixing layer
31 develops around the vegetation height ($y \approx h_v$), as reported
32 for submerged vegetation flow by Nepf (2012) and Okamoto
33 and Nezu (2013). Downstream of the rigid, submerged veg-
34 etation patch (Case R2), the vertical momentum transport by
35 TM ($-\overline{uv}$) is greater than the spanwise one ($-\overline{uw}$). Conse-
36 quently, the flow velocity first starts to increase around the
37 vegetation tips and the velocity shear ($\partial U/\partial y$) gradually de-
38 creases as the x -coordinate increases [Fig. 9(a)]. Vertical
39 vortices develop over the flexible, submerged vegetation
40 (Case F) as well, but their contributions to the momentum
41 transport ($-\overline{uv}$) are much smaller than those in Case R2. The
42 difference between rigid and flexible vegetation flows may
43 be attributed to the decrease in the velocity difference across
44 the mixing layer [Fig. 12]. The streamwise distributions of
45 the vertical momentum transfers T_y [defined by Eq. (15a)]
46 are shown in Fig. 19(d). This confirms that the momentum
47 transport into the vegetation patch wake region in Case R2
48 is dominated by vertical vortices ($-\overline{uv}$) and flow redistribu-
49 tion across the vegetation height ($-UV$). In addition, com-
50 parison between Figs. 19(b) and 19(d) also demonstrates that
51 the weak development of vertical vortices enhances the im-
52 portance of the spanwise momentum transport by the sec-
53 ondary flow in Case F ($-UW$). The streamwise flow veloc-
54 ity rapidly increases in the streamwise direction near the

55 channel bed at $x/H = 6-7$, while U increases more
56 slowly around the vegetation height, resulting in the negative
57 velocity shear ($\partial U/\partial y < 0$) near the channel bed [Fig. 9(a)].

58 D. Relationship between vortex structure and sedi- 59 ment deposition

60 The results of the sediment deposition experiments sug-
61 gest that the spatial pattern of the sediment deposition re-
62 flects the vortex and secondary flow structures around a veg-
63 etation patch. There are two conflicting effects of the flow
64 structure on the fine sediment transport around vegetated re-
65 gions: (i) resuspension of on-bed sediment particles (Lu et
66 al., 2021) and (ii) transport of suspended sediment (Kingora
67 and Sadat, 2022). Regarding the former factor, many previ-
68 ous studies pointed out that the turbulent kinetic energy
69 (TKE) is an important parameter to evaluate the bed shear
70 stress within and around vegetated areas (Ortiz et al., 2013;
71 Xiang et al., 2023; Yang and Nepf, 2018). The TKE k is
72 calculated from the three-component velocity data as fol-
73 lows:

$$74 \quad k \equiv 0.5(\overline{u^2} + \overline{v^2} + \overline{w^2}) \quad (16)$$

75 Since the flow direction is three-dimensional in vegetated
76 channels, the bed shear stress τ_0 can be estimated by the
77 TKE near the channel bed (Pope et al., 2006; Marjoribanks
78 et al., 2019):

$$79 \quad \tau_0 = C_1 \rho k \quad (17)$$

80 Here, C_1 is a non-dimensional coefficient, found to be
81 $C_1 = 0.19-0.3$ (Baranya, 2012; Pope et al., 2006). When τ_0
82 is greater than the critical shear stress ($\tau_0 > \tau_c = \rho u_{*c}^2$, i.e.,
83 $k > u_{*c}^2/C_1$), sediment particles on the channel bed start to
84 move and the riverbed will be eroded. This suggests that the
85 development of vertical and horizontal vortices around a
86 vegetation patch determines the enhanced or reduced depo-
87 sition areas, but the secondary flow structure does not.

88 Figures 20(a) and 20(b) show the streamwise distribu-
89 tions of the near-bed TKE at the patch centerline ($x/H >$
90 4.9; $y/H = 0.07$; $z/b_p = 0$) and the $k-c$ plot for Cases
91 R1, F and R2, respectively. The enhanced deposition area
92 ($c > c_0$) is observed in the regions where the TKE is smaller
93 than $k = 5.0u_{*c}^2$ ($= u_{*c}^2/C_1$ where $C_1 = 0.14$). These ar-
94 eas correspond to the regions just downstream of a vegeta-
95 tion patch for all cases and far downstream of the flexible
96 vegetation patch ($x/H > 7$ in Case F). Here, the value of
97 C_1 was determined based on the critical TKE measured in
98 Fig. 20(b). The reason why the measured C_1 was smaller
99 than that presented in the previous studies is probably that
100 the values of TKE determining τ_0 by Eq. (17) were overes-
101 timated since the reference height of TKE ($y/H = 0.07$)
102 was not sufficiently close to the channel bed. Nevertheless,
103 the regions with large and small TKE coincide with the re-
104 duced ($k > u_{*c}^2/C_1$; $c < c_0$) and enhanced deposition areas
105 ($k < u_{*c}^2/C_1$; $c > c_0$), respectively, confirming that the sed-
106 iment deposition areas around a vegetation patch are

determined by the vertical and horizontal mixing layers (Ortiz et al., 2013; Liu et al., 2018).

On the other hand, as well as the momentum transport mechanisms discussed in 4.2, the suspended sediment transport into the patch wake region is governed by both turbulent mixing and advection (secondary flow). The sediment transfer into the patch wake region consists of the vertical transport across the vegetation height ($y = h_v$) and the spanwise transport across the lateral patch edge ($z = b_p$). Each of the vertical and spanwise sediment transfers can be decomposed into contributions from convection ($-CV$, $-CW$) and diffusion ($-\overline{c'v}$, $-\overline{c'w}$), where C and c' are the time-averaged and turbulent fluctuating components of the sediment concentrations, respectively. Thus, the turbulence and secondary flow structures are likely to determine the sediment transport flux and the sediment concentration distribution and to affect the amount of sediment deposition behind a vegetation patch.

The k - c plot map [Fig. 20(b)] also shows that there is significant variation in the amount of sediment deposition in the enhanced deposition areas with small TKE ($c > c_0$; $k < u_c^2/C_1$). Specifically, the sediment deposition is noticeably enhanced far downstream of the flexible vegetation patch ($x/H > 7$) [Fig. 17]. In this region, the spanwise flows caused by the strong secondary flows from both lateral patch edges converge [Fig. 13(a)] and the horizontal mixing layers are decaying near the channel bed [Fig. 14(a)]. Consequently, the secondary flows ($W < 0$ in $z > 0$ near the channel bed) increase the sediment transport flux to the vegetation patch wake region ($-CW > 0$) without developing turbulence or disturbing the sediment deposition on the channel bed. In contrast, within $x/H > 6$ in Cases R1 and R2, fine sediment deposition on the channel bed is prevented by the strong near-bed turbulence and the sediment particles are transported in the vertical or spanwise directions by the vertical and horizontal vortices ($-\overline{c'v}$; $-\overline{c'w}$).

The present study investigates the momentum and sediment transport mechanisms around rigid and flexible vegetation patches, focusing on the effects of the vegetation flexibility on turbulent and secondary flow structures. Figure 21 illustrates the observed variations in flow structure and sediment deposition areas behind a vegetation patch due to submergence and vegetation flexibility. The horizontal vortices ($-\overline{uw}$) develop around the lateral patch edges ($z \approx \pm b_p$) and determine the wake region behind the rigid, emergent vegetation patch (R1), while the vertical vortices near the vegetation tips ($-\overline{uv}$) are the most important factor that characterizes the mass and momentum transport around the rigid, submerged vegetation patch (R2). In contrast, neither vertical nor horizontal vortices significantly develop around the flexible, submerged vegetation patch (F). This is partly because the velocity shears in the mixing layers ($\partial U/\partial y$ or $\partial U/\partial z$) are smaller than those in Cases R1 and R2 due to the decrease in the flexural rigidity of vegetation elements.

However, strong secondary flows are formed around deflected vegetation elements at the lateral patch edges and enhance the momentum transfer to the patch wake region in the spanwise direction. The results also imply the development of secondary flows in Cases R1 and R2, but their contributions to the momentum and sediment transport are much less than those of the turbulent mixing.

V. CONCLUSIONS

The present study explores the effects of vegetation flexibility on vortex structure and sediment dynamics through flume measurement of flow velocities and sediment erosion and deposition for rigid and flexible vegetation patch flows. The PIV measurement for vertical and horizontal planes enables us to capture the secondary flow structure downstream of the vegetation patch and to understand its importance in mass and momentum transport. Moreover, the results of the sediment deposition experiments suggest a strong connection between the vortex structure and the enhanced deposition areas in the vegetation patch wake region. The key findings are as follows:

1. On the sides of the single inclined vegetation element, downward flows are generated by local pressure gradient along the vegetation element surface. Afterwards, upwards flows occur and transport high-momentum fluid behind the inclined vegetation element. As a result, the velocity shear ($\partial U/\partial y$) and the vertical Reynolds shear stress ($-\overline{uv}$) behind the inclined vegetation element are much smaller than those behind the upright vegetation element. The three-dimensional flow structure is also observed around single- and three-row patches of inclined blades and enhanced by the number of strip elements in the streamwise and spanwise directions.
2. In the rigid, emergent vegetation patch flow (R1), horizontal vortices ($-\overline{uw}$) develop around the lateral patch edge ($z \approx b_p$) and expand to the patch centerline, while vertical vortices ($-\overline{uv}$) dominate momentum transport over the rigid, submerged vegetation patch (R2). The development of vortex structures is observed around the flexible vegetation patch (F) as well, but the positive Reynolds stresses ($-\overline{uv} > 0$) are distributed only around the deflected vegetation height. On the other hand, the streamwise flow velocity increases rapidly and thereby the velocity shear becomes negative ($\partial U/\partial y < 0$) near the channel bed behind the flexible vegetation patch. This indicates that the near-bed flow structure is characterized by horizontal momentum transport processes due to horizontal vortices and secondary flows.

13. Around the lateral edge of a flexible, submerged vegetation patch (F), the spanwise flow velocity is positive near the deflected vegetation height and negative near the channel bed. The three-dimensional flow structure indicates that the deflection of vegetation elements causes geometric change in the boundary condition and develops a strong secondary flow structure around the flexible vegetation patch. This secondary flow results in the rapid re-acceleration of the streamwise flow velocity near the bed and the negative vertical velocity shear ($\partial U / \partial y < 0$) in the vegetation patch wake region. In contrast, downstream of the submerged rigid vegetation patch (R2), the momentum transport by the vertical vortices ($-\overline{uv}$) induces weak secondary flow that rotates in the opposite direction to that in Case F.

14. The development of the vertical and horizontal vortices characterizes the streamwise distribution of TKE near the channel bed and the fine sediment deposition areas in a vegetation patch wake region. In the rigid vegetation cases (R1 and R2), the enhanced deposition area is distributed just behind the vegetation patch, and downstream of this region, no sediment deposition is observed because the vertical or horizontal vortices prevent the suspended fine sediment from being deposited on the channel bed. On the other hand, in the flexible vegetation case (F), the near-bed TKE is small and instead the secondary flows contribute to the sediment transport to the patch wake region. As a result, the deposition areas and the amount of sediment deposition behind the flexible vegetation patch are larger than those in Cases R1 and R2.

To further understand and verify the adequacy of the phenomenological model, the influence of hydraulic conditions and wide range of vegetation parameters (e.g., the submergence depth ratio; the Cauchy number) need to be investigated in future work. Moreover, we focused only on the inclination of flexible vegetation elements in this study, but the effects of oscillation of vegetation elements on the turbulence and secondary flow structures should be investigated. Nevertheless, the results of the present experimental data provide new insight into the vortex and secondary flow structures and their effects on the sediment deposition around vegetation patches with different submergence and flexibility characteristics.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

Kazumasa Matsumoto: Conceptualization (equal); Data curation (lead); Formal analysis (equal); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (equal); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Taka-aki Okamoto:** Conceptualization (equal); Formal analysis (equal); Investigation (lead); Methodology (lead); Resources (equal); Supervision (equal); Visualization (equal); Writing – original draft (supporting); Writing – review & editing (equal). **Michio Sanjou:** Formal analysis (equal); Methodology (lead); Resources (equal); Supervision (equal); Writing – review & editing (equal). **Timothy I. Marjoribanks:** Conceptualization (equal); Methodology (lead); Writing – review & editing (equal). **Masashi Takada:** Investigation (supporting); Methodology (supporting); Visualization (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOMENCLATURE

a	Vegetation density
A	Total frontal area of vegetation elements
A_b	Reference bed area of a vegetation patch
b	Spanwise width of a vegetation element
B	Channel width
b_D	Half-width of a vegetation patch
B_v	Spanwise interval of vegetation elements
c	Sediment deposition weight per unit area
C	Time-averaged sediment concentration
c'	Fluctuating component of the instantaneous sediment concentration
c_0	Sediment deposition weight per unit area over the smooth bed
Ca	Cauchy number
C_D	Drag force coefficient
C_f	Friction coefficient
$C_{\log}$	Constant in the log-law profile
d	Mean diameter of the silica sand particles
E	Bending elastic modulus of a vegetation element
Fr	Froude number ($= U_m / (gH)^{0.5}$)

F_u	Flatness ($F_u = \overline{u^4}/(\overline{u'})^4$)
g	Gravitational acceleration
h	Non-deflected vegetation height
H	Flow depth
h_d	Deflected vegetation height
h_v	Vegetation height in flow
I	Second moment of area of a vegetation element ($= bt_v^3/12$)
k	Turbulent kinetic energy (TKE)
L_{HV}, L_{VV}	Wake-lengths based on the horizontal and vertical vortices
L_D	Streamwise length of a vegetation patch
n_v	Number of vegetation elements in a vegetation patch
Q	Flow discharge
Re	Reynolds number ($= U_m H/\nu$)
Re_b	Stem Reynolds number ($U_{patch} b/\nu$)
s	Specific gravity of silica sand in water
S_u	Skewness ($= \overline{u^3}/(\overline{u'})^3$)
S_δ	Growth rate of a shear layer
t_v	Thickness of a vegetation element
u_*	Friction velocity
$\bar{U}$	Averaged velocity across a shear layer
ΔU	Velocity difference across a shear layer
U^+	Inner-scaled mean flow velocity
U_∞	Maximum flow velocity
U_a	Approaching flow velocity
U_e	Bleed flow velocity
U_m	Bulk-mean flow velocity ($\equiv Q/BH$)
U_{patch}	Mean flow velocity within a vegetation patch
u, v, w	Fluctuating components of the streamwise, vertical and spanwise flow velocities
U, V, W	Time-averaged components of the streamwise, vertical and spanwise flow velocities
u', v'	Streamwise and vertical turbulent intensities
V_0	Canopy volume
V_t	Settling velocity of silica sand particles
x, y, z	Streamwise, vertical and spanwise coordinates
x_d	Streamwise position of a vegetation tip
y^+	Inner-scaled vertical coordinate
γ_0, γ_1	Model coefficients in Eq. (9)
Γ_D	Patch blockage parameter
δ	Boundary layer thickness
κ	Von Karman constant
ν	Kinematic viscosity of water
ρ	Density of water
σ	Density of silica sand
τ_0	Bed shear stress
τ_{0c}	Critical bed shear stress
ϕ	Solid volume fraction of a vegetation patch ($\equiv (bt_v h)/(L_v B_v h_v)$)

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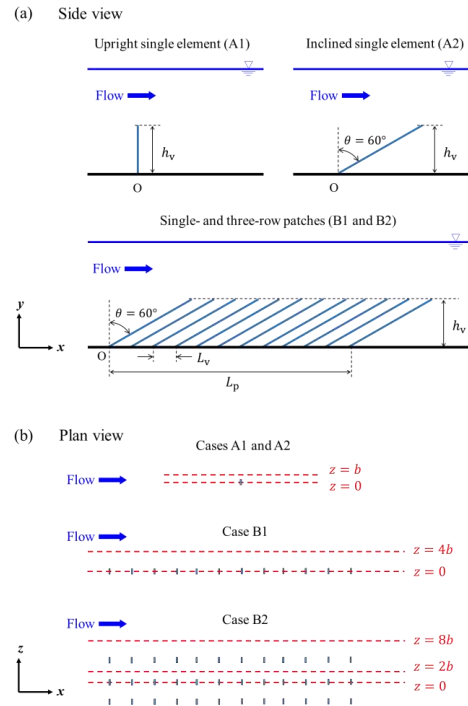


FIG. 1. Outline of experimental setups for the upright (A1) and inclined (A2) single blade elements and for the single- (B1) and three-row (B2) patches of inclined elements: (a) a side view and (b) a plan view.

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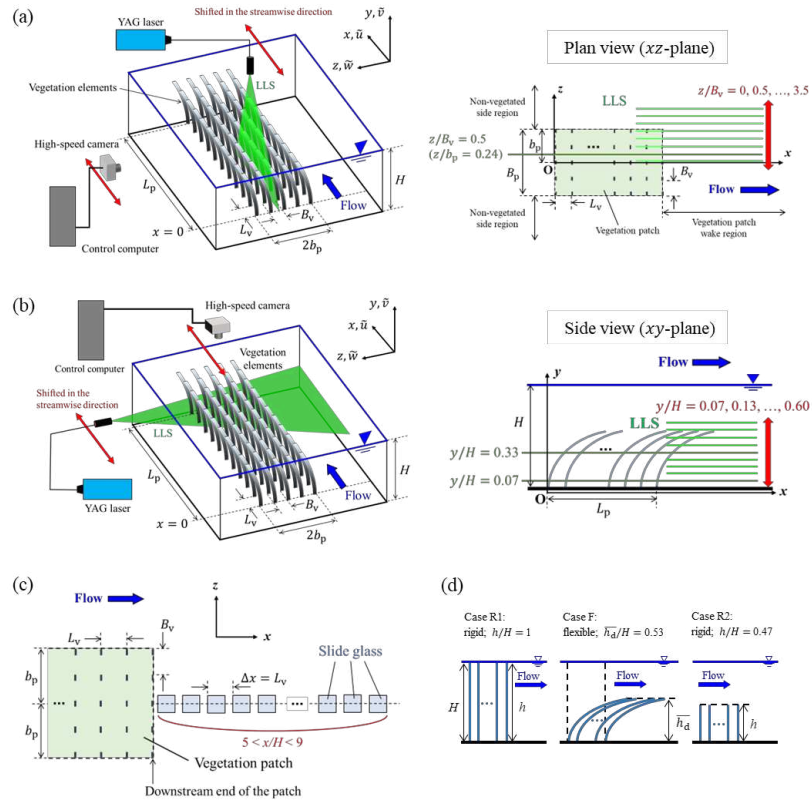


FIG. 2. Experimental setup for vegetation patch flows: (a) PIV measurements in a vertical plane; (b) PIV measurements in a horizontal plane; (c) sediment deposition experiment for the patch wake region; (d) schematic view of the rigid and flexible vegetation models in Case R1, F, and R2.

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TABLE I. Experimental conditions.

Case	U_m (m/s)	H (m)	Re	Fr	L_p (m)	B_p (m)	h (m)	h_v (m)	h_v/H	n_v	a (m ⁻¹)	Ca
Smooth	0.25	0.15	37,500	0.21	—	—	—	—	—	0	—	—
Rigid blade elements												
A1	0.25	0.15	37,500	0.21	—	—	0.070	0.070	0.47	1	—	4.7×10^{-3} (Rigid)
A2					—	—	0.140	0.070	0.47	1	—	3.8×10^{-2} (Rigid)
B1					0.352	0.008	0.140	0.070	0.47	1×12	—	3.8×10^{-2} (Rigid)
B2					0.352	0.072	0.140	0.070	0.47	3×12	7.8	3.8×10^{-2} (Rigid)
Wide vegetation patch												
R1	0.25	0.15	37,500	0.21	0.736	0.136	0.150	0.150	1 (Emergent)	5×24	7.8	4.6×10^{-2} (Rigid)
F							0.150	0.080	0.53 (Submerged)			36 (Flexible)
R2							0.070	0.070	0.47 (Submerged)			4.7×10^{-3} (Rigid)

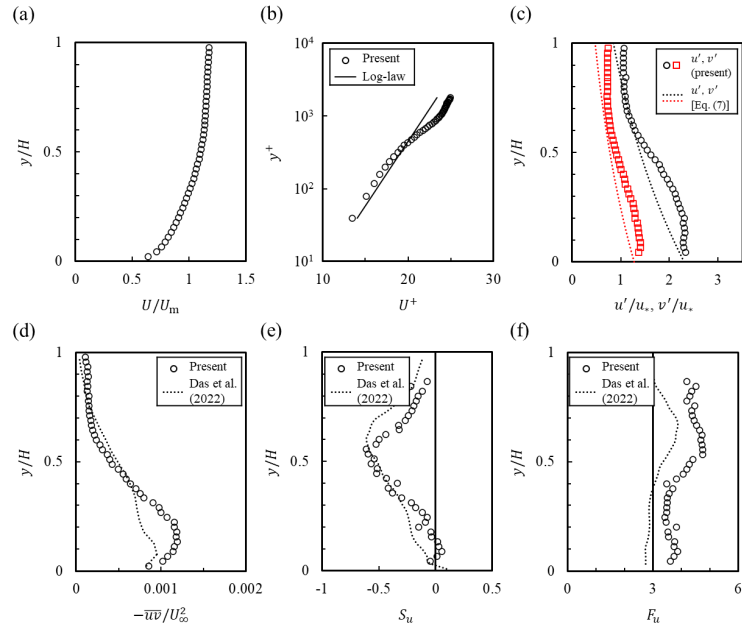


FIG. 3. Validation of the smooth bed flow 4 m downstream of the flume inlet: (a) time-averaged streamwise flow velocity (U); (b) semi-log plot of the velocity profile ($U^+(y^+)$); (c) streamwise and vertical turbulence intensities, (u' and v'); (d) Reynolds shear stresses ($-\overline{u'v'}$); (e) skewness (S_u) and (f) flatness (F_u).

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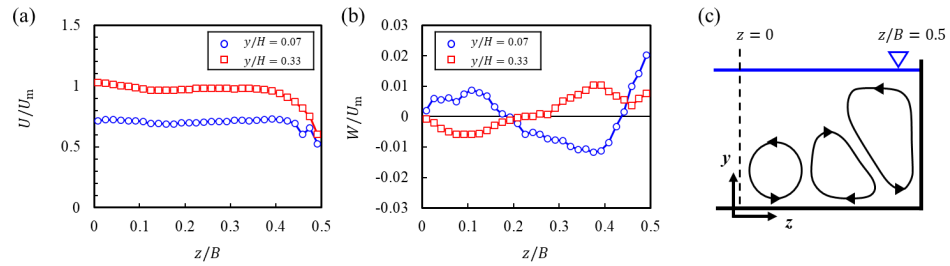


FIG. 4. Spanwise distributions of (a) U and (b) W at $y/H = 0.07$ and 0.33 ($x = 4$ m) and (c) schematic diagram of the rotating cells in the cross-sectional (yz -) plane for the smooth bed flow.

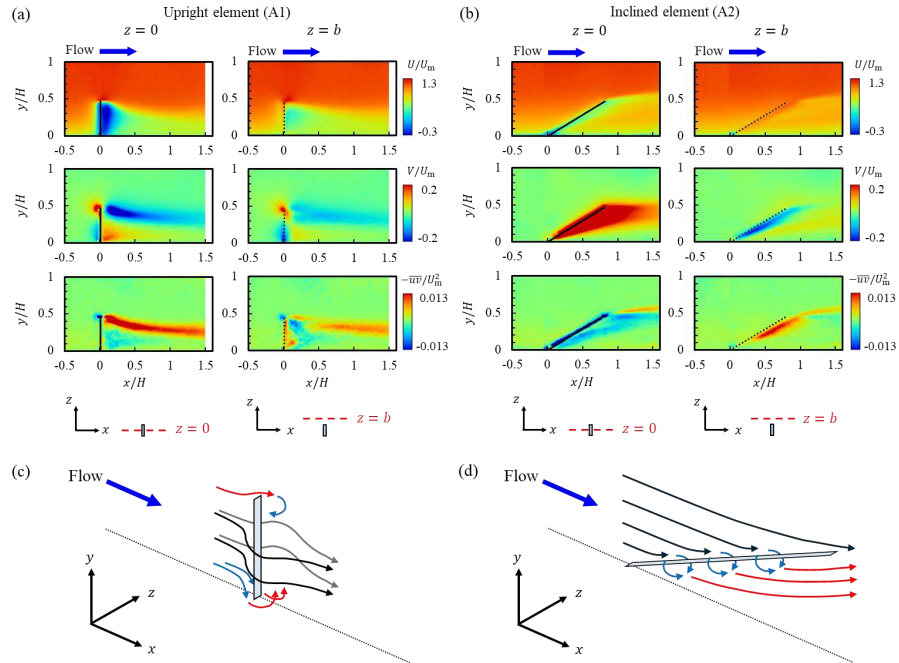


FIG. 5. (a, b) Results of the velocity measurements for (a) the upright (Case A1) and (b) inclined (Case A2) single vegetation elements at $z=0$ and $z=b$: the time-averaged streamwise flow velocity U , the time-averaged vertical flow velocity V , and the vertical Reynolds shear stress $-\overline{uv}$; (c, d) schematic diagrams of the flow structure around the (c) upright (A1) and (d) inclined (A2) vegetation elements.

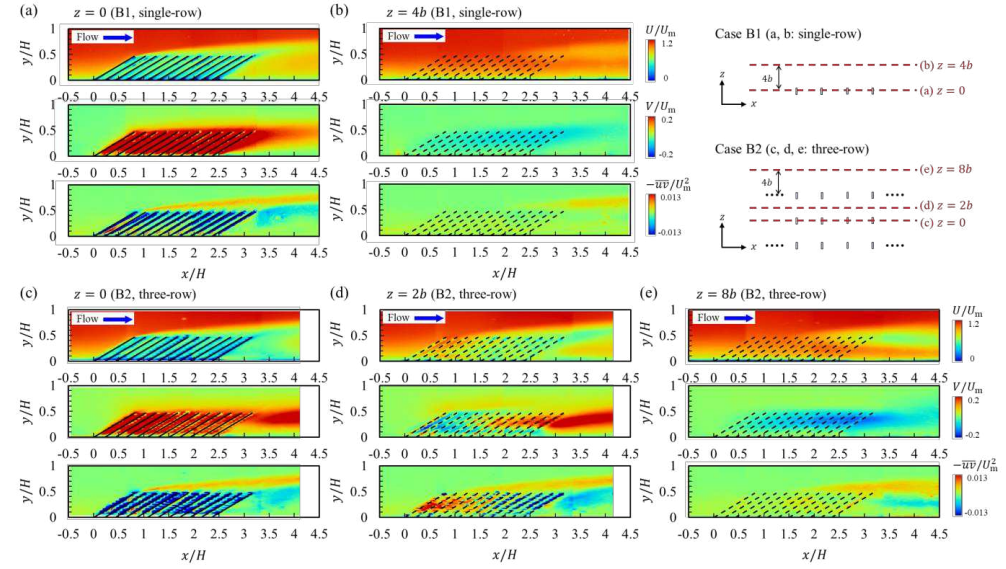


FIG. 6. Results of the velocity measurements for the single-row patch of inclined vegetation elements (Case B1) at (a) $z = 0$ and (b) $z = 4b$ and for the three-row patch (Case B2) at (c) $z = 0$, (d) $z = 2b$, and (e) $z = 8b$: the time-averaged stream-wise flow velocity U ; the time-averaged vertical flow velocity V ; the vertical Reynolds shear stress $-\overline{u'v'}$.

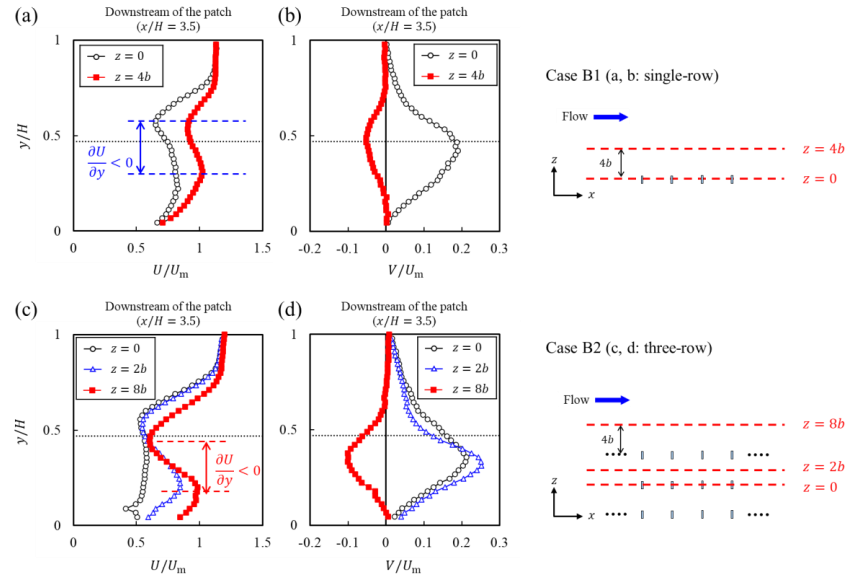


FIG. 7. Vertical distributions of the (a, c) streamwise and (b, d) vertical flow velocities at $x/H = 3.5$ for the (a, b) single-(B1) and (c, d) three-row (B2) patch flows.

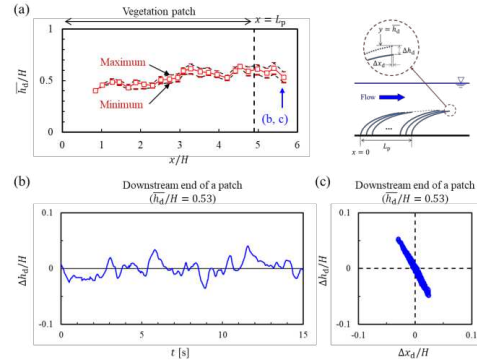


FIG. 8. Displacement of vegetation elements for Case F: (a) time-averaged vegetation tip positions $(\bar{x}_d, \bar{h}_d)$ at the patch centerline ($z = 0$); (b) time-series of the vertical displacement and (c) tip trajectory of the vegetation element at the downstream patch end ($x = L_p$).

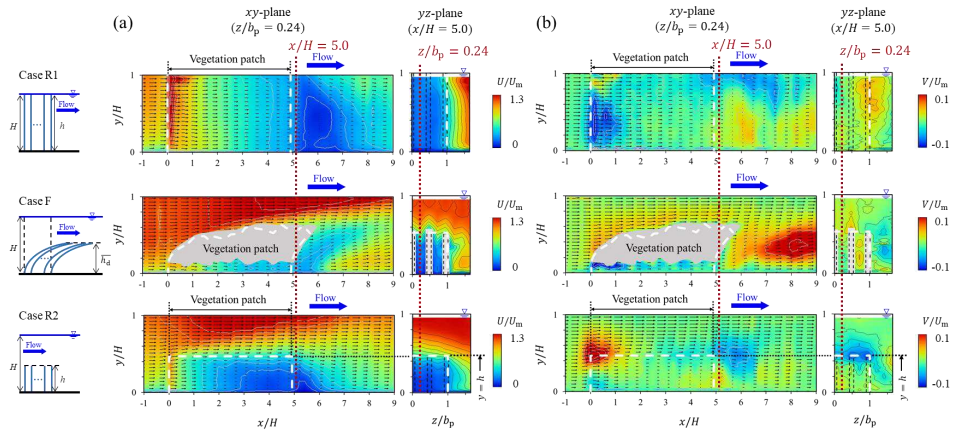


FIG. 9. Contour maps for a longitudinal (xy -) plane at $z/b_p = 0.24$ and a cross-sectional (yz -) plane at $x/H = 5.0$: (a) the time-averaged streamwise flow velocity U ; (b) the time-averaged vertical flow velocity V .

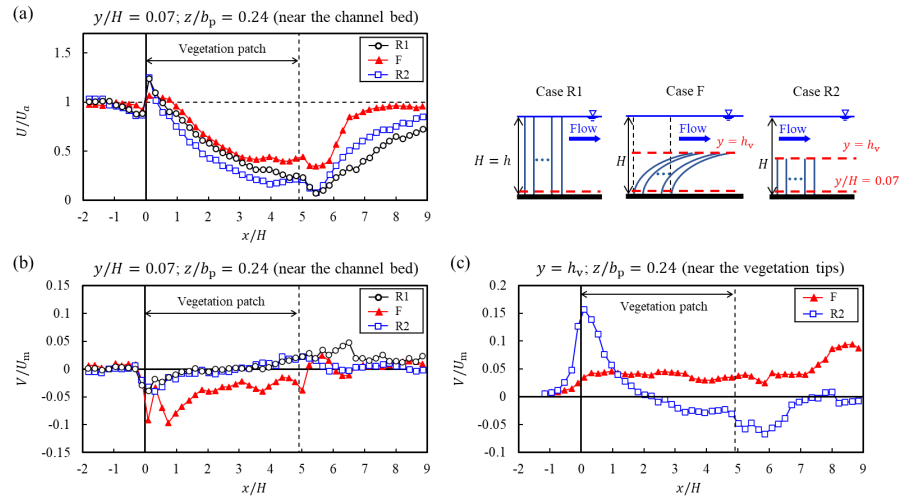


FIG. 10. Streamwise distributions of the time-averaged flow velocities at the patch centerline ($z/b_p = 0.24$): (a) the streamwise flow velocity U near the channel bed ($y/H = 0.07$); the vertical flow velocity V (b) near the channel bed for Cases R1, F, and R2 ($y/H = 0.07$) and (c) near the vegetation tips for Cases F and R2 ($y = h_v$).

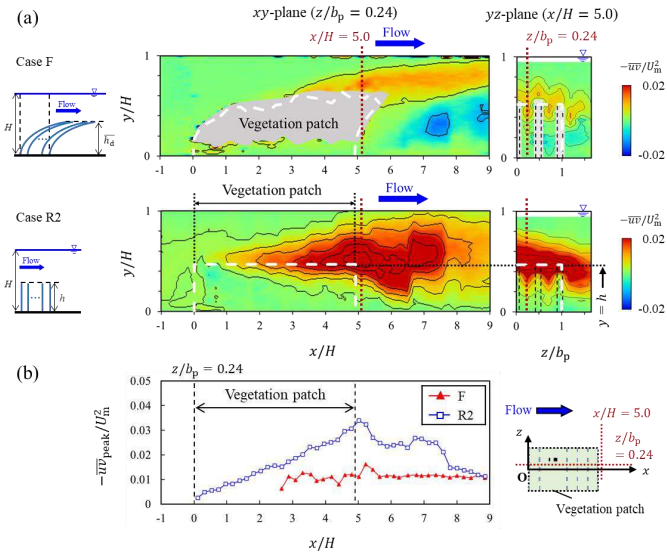


FIG. 11. Spatial evolution of the vertical mixing layer for submerged vegetation cases (Cases F and R2): (a) contour maps of the vertical Reynolds shear stress $-\overline{u'v'}$ for a longitudinal (xy-) plane at $z/b_p = 0.24$ and a cross-sectional (yz-) plane at $x/H = 5.0$; (b) streamwise distributions of the peak vertical Reynolds stress $-\overline{u'v'}_{\text{peak}}$ at the patch centerline ($z/b_p = 0.24$).

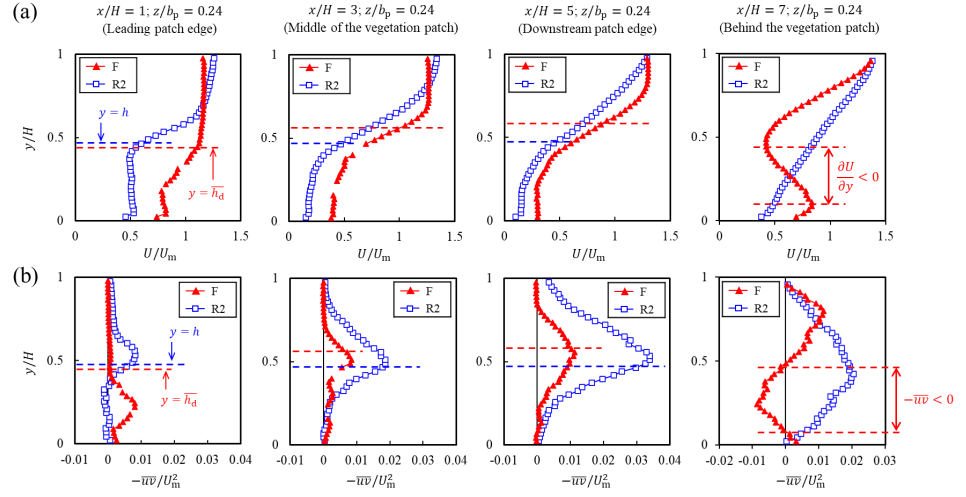


FIG. 12. Vertical distributions of the (a) streamwise flow velocity U and (b) vertical Reynolds stress $-\overline{u'v'}$ at $x/H = 1, 3, 5$, and 7 ($z/b_p = 0.24$) for Cases F and R2.

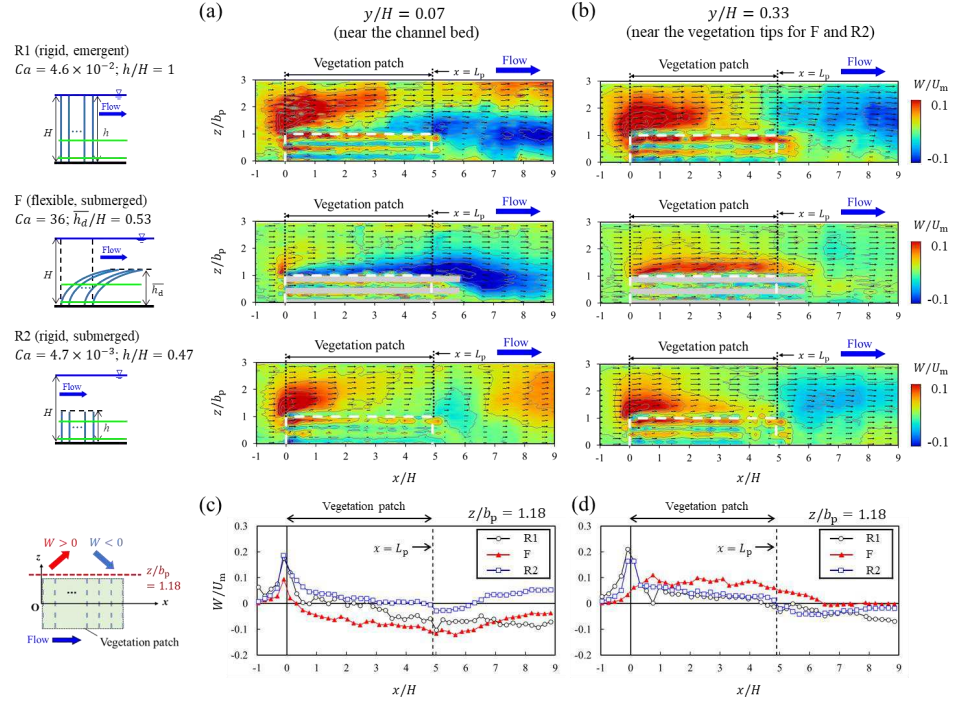


FIG. 13. Spatial distributions of the time-averaged spanwise flow velocity W at heights of (a, c) $y/H = 0.07$ and (b, d) $y/H = 0.33$: (a, b) contour maps for horizontal (xz -) planes; (c, d) streamwise distributions at $z/b_p = 1.18$. The white dashed lines in the contour maps represent the outline of the vegetation patch.

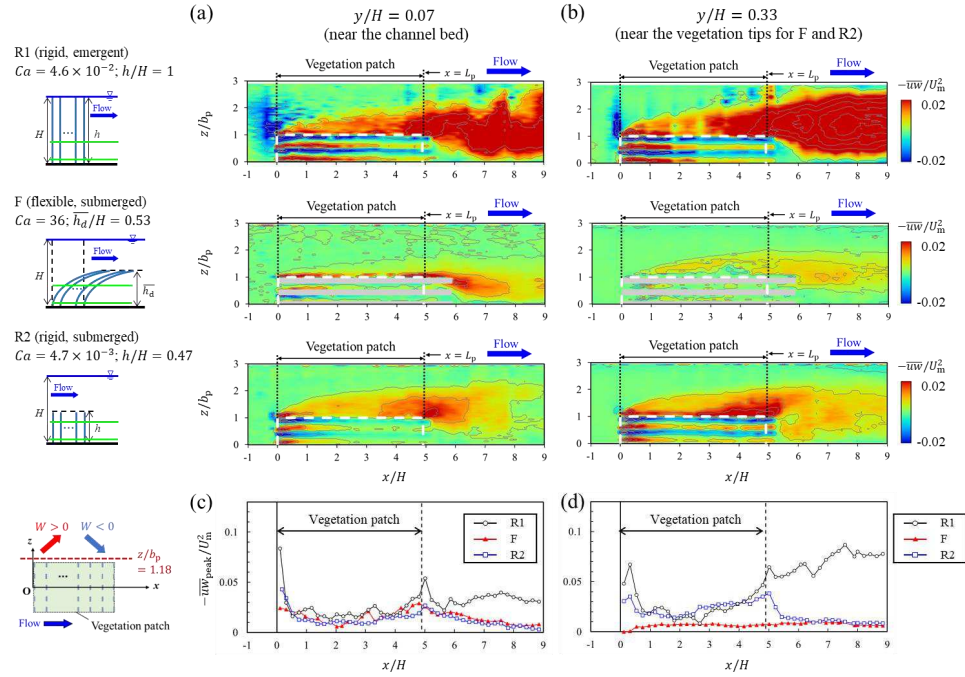


FIG. 14. Spatial distributions of the horizontal Reynolds shear stress $-\overline{u'w'}$ at heights of (a, c) $y/H = 0.07$ and (b, d) $y/H = 0.33$: (a, b) contour maps for horizontal (xz -) planes; (c, d) streamwise distributions of the peak horizontal Reynolds stress $-\overline{u'w'}_{\text{peak}}$.

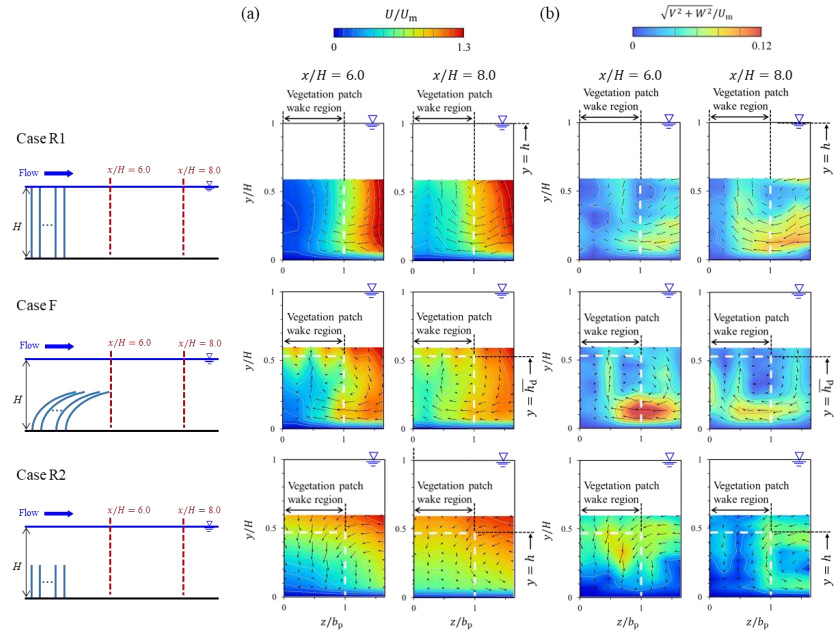


FIG. 15. Contour maps of (a) the time-averaged streamwise velocity U and (b) the magnitude of secondary flow ($\sqrt{V^2 + W^2}$) for cross-sectional (yz -) planes downstream of the vegetation patch ($x/H = 6.0$ and 8.0). The black arrows represent the secondary flow vectors (V, W) .

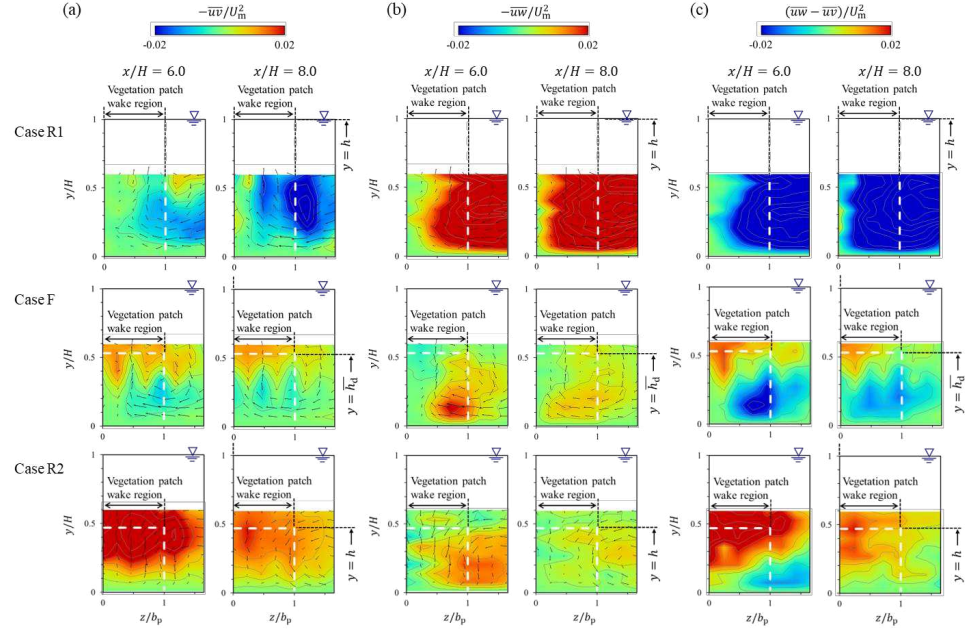


FIG. 16. Contour maps of (a) the vertical Reynolds shear stress $-\overline{uv}$, (b) the horizontal Reynolds shear stress $-\overline{uw}$, and (c) the difference between the vertical and horizontal components $(\overline{uw} - \overline{uv})$ for cross-sectional (yz -) planes downstream of the vegetation patch ($x/H = 6.0$ and 8.0).

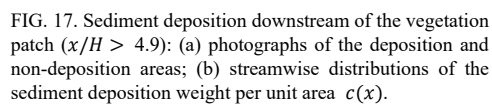


FIG. 17. Sediment deposition downstream of the vegetation patch ($x/H > 4.9$): (a) photographs of the deposition and non-deposition areas; (b) streamwise distributions of the sediment deposition weight per unit area $c(x)$.

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TABLE II. Comparison of the blockage parameters and the ratios of the bleed flow velocity to the approaching velocity for Cases F and R2.

	U_{patch}/U_a	C_D	Γ_D	U_e/U_a (measured)	U_e/U_a (predicted)
F	0.645	1.01	1.07	0.346	0.039
R2	0.468	1.29	1.37	0.078	0.044

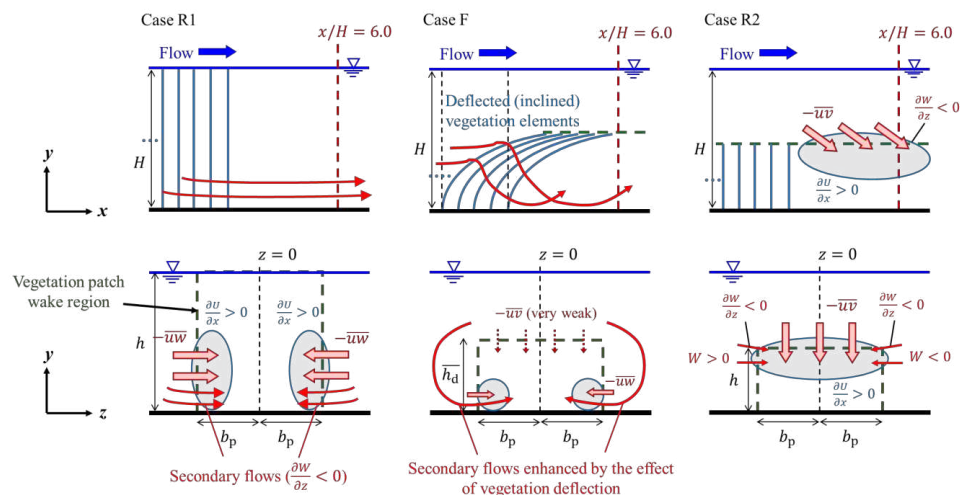


FIG. 18. Schematic diagrams of the formation mechanisms of the secondary flow structure behind the vegetation patch.

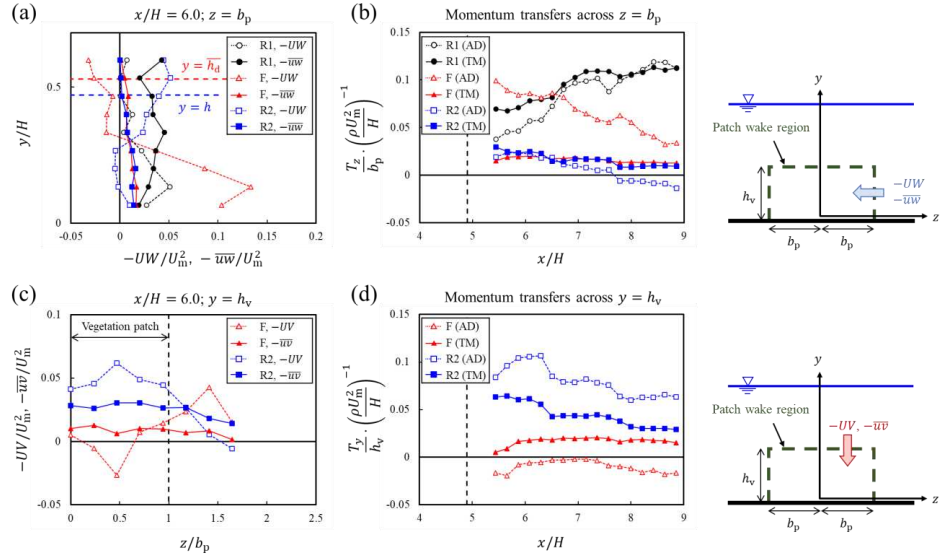


FIG. 19. Momentum transfers to the vegetation patch wake region: (a) vertical distributions of the spanwise momentum transport ($-UW$ and $-uW$) at $x/H = 6.0$ and $z = b_p$; (b) streamwise distributions of the spanwise momentum transfers T_z across $z = b_p$ by advection (AD) and turbulent mixing (TM); (c) spanwise distributions of the vertical momentum transport ($-UV$ and $-uV$) at $x/H = 6.0$ and $y = h_v$; (d) streamwise distributions of the vertical momentum transfers T_y across $y = h_v$ by AD and TM.

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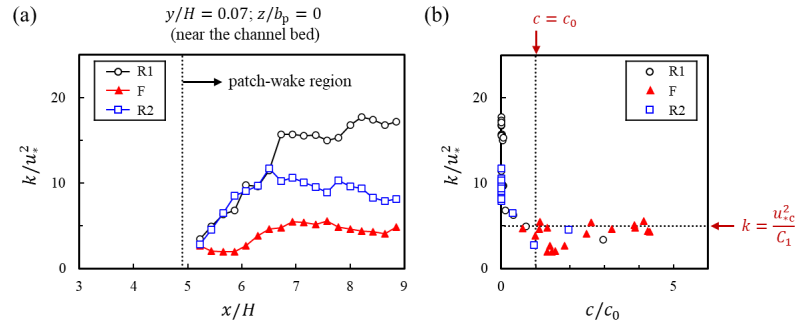


FIG. 20. (a) Streamwise distributions of the TKE k in the patch wake region; (b) comparison between the TKE and the sediment deposition weight per unit area.

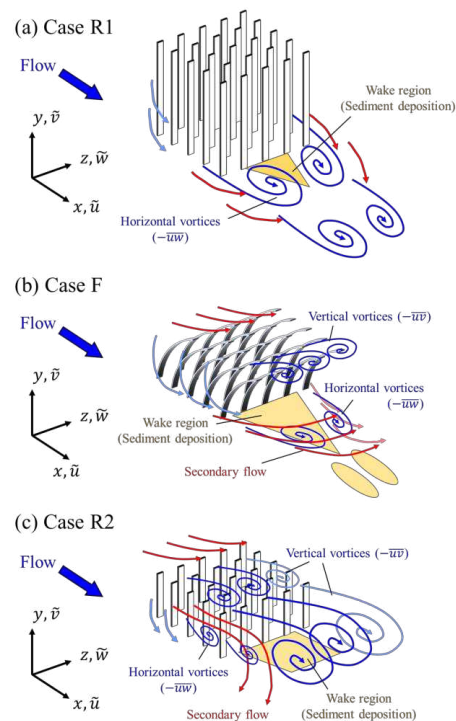


FIG. 21. Schematic diagram of vortex structure and sediment deposition area behind the flexible and rigid vegetation patches.