

PARTICLE ENTRAINMENT BY BURSTING PHENOMENA IN OPEN-CHANNEL FLOW OVER ROUGH BED

By Kazumasa Matsumoto¹, Taka-aki Okamoto² and Michio Sanjou³

¹*Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto 615-8540, Japan*

²*Department of Civil Engineering, Meijo University, Nagoya 468-8502, Japan*

³*Disaster Prevention Research Institute, Kyoto University, Kyoto 612-8235, Japan*

Corresponding e-mail: matsumoto.kazumasa.85s@kyoto-u.jp

ABSTRACT

In natural gravel-bed rivers, fine sediment deposition contributes to the bed morphology and entrapment of plant seeds often leads to the evolution of vegetated areas. Therefore, it is important to understand the transport mechanisms of fine particles between and over large-grain gravels. The present work explores influence of the bursting phenomena on transport of fine grain particles between roughness elements through laboratory experiments. The rough bed consists of hemispherical elements fixed to the flume bed to mimic a natural gravel riverbed. First, two-components of flow velocity within and over the rough bed were measured by particle image velocimetry (PIV) combined with refractive-index matching (RIM). This visualizing method reveals the complex flow structure in a valley of the rough bed; especially, the formation of a horseshoe-shaped vortex at the upstream side of a roughness element. The linear stochastic estimation (LSE) of the conditional velocity field given an upward flow event near the channel bed demonstrates that the horseshoe vortex is temporarily enhanced after a high-momentum flow passes over the roughness crest and a sweep impinges onto the roughness surface. Next, the simultaneous analysis of particle trajectories and flow velocities was performed for some particle entrainment events between roughness elements. Most upward particle motions in the near-bed region are initiated by the upward flow induced by sweep and terminate below the roughness height. On the other hand, some of the particles lifted by sweep are transported beyond the roughness height by a following ejection event.

Keywords: particle entrainment, bursting phenomena, refractive index matching (RIM), PIV, and rough-bed flow

1 **Statements and Declarations**

- 2 • **Competing Interests:** The authors have no competing interests to declare that are relevant to
3 the content of this article.

4 **Author Contributions**

5 Kazumasa Matsumoto and Taka-aki Okamoto substantially contributed to the study
6 conceptualization. Taka-aki Okamoto and Michio Sanjou significantly contributed to data analysis
7 and interpretation of the results. Kazumasa Matsumoto drafted the original manuscript. All authors
8 critically reviewed and revised the manuscript draft and approved the final version for submission.

9 **ORCID iD**

10 Kazumasa Matsumoto: <https://orcid.org/0009-0002-9931-5514>

11 Taka-aki Okamoto: <https://orcid.org/0000-0001-6801-4335>

12 Michio Sanjou: <https://orcid.org/0000-0002-8146-9788>

1. Introduction

It is well-known that particle transport phenomena by turbulent flow play a key role in characterizing riverine ecosystem. Deposition of fine sediments into gravel bed leads to geomorphic development and some changes in habitat for aquatic organisms (Harper et al. [19]; Casas-Mulet et al. [10]). Seeds of various plants are conveyed by flood and retained between bed-gravels together with sediment particles, which often results in expansion of vegetation area (Gage & Cooper [18]). Therefore, there are many studies exploring the coherent structure of turbulent flow and its effects on particle entrainment or entrapment in open-channel flow over rough bed.

A number of studies have explored the complex mean and turbulent flow structure over rough bed due to the bed topography. To consider the heterogeneity of flow, the double averaging method (DAM) was proposed by Nikora et al. [32], where the time-averaged properties are further spatially averaged to set off the grain-scale spatial variation in flow structure. On the other hand, the momentum transport mechanism around each roughness element has been also investigated in experimental studies using particle image velocimetry (PIV) and in numerical simulations (Coccal et al. [11]; Pokrajac & Manes [41]; Bomminayuni & Stoesser [6]; Fang et al. [17]). Their results suggest the existence of the coherent structure over rough bed, which contains various types of vortices called hairpin-shaped, horseshoe-shaped vortices, and so on, and its importance in mass and momentum transport. Moreover, results of long-duration PIV by Cameron et al. [8] suggest that there exist two types of large-scale structures called large-scale motion (LSM) and very large-scale motion (VLSM) over rough bed. These investigations focused on the large-scale flow structure over rough bed and the small-scale flow structure near each roughness element, thus suggesting the development of the coherent structure of turbulence in each flow field. Yet, they lack sufficient data for the flow velocities between roughness elements because of difficulty in velocity measurements, and have not fully revealed the interaction between the flow fields over and within rough bed.

Another central question is what influences the coherent structures have on particle transport in the boundary layer, especially on particle entrainment from the bed. Classical methods to calculate bedload transport have scaled sediment transport with flow discharge or mean shear stress, but their accuracy is often limited because they are not based on microscale phenomenon and heterogeneity in flow structure and bed topography (Dey & Ali [13]; Pähtz et al. [38]; Ancey [3]). To improve the existing approaches, it is essential to deepen understanding of the interaction between turbulence and particle behaviors (entrainment, upward and downward motions). Some

1 pioneering works made detailed observations of the particle motion near the channel wall,
2 indicating the strong connection between particle motion and the coherent structures (Sumer &
3 Oğuz [47]; Rashidi et al. [43]; Niño & García [33]; Sechet & Le Guennec [45]). Specifically, the
4 initiation of a particle lift-up is relevant to the upward transport of low-momentum fluid called
5 ‘ejection’ and the downward transport of high-momentum fluid called ‘sweep’. Such coherent fluid
6 motions are called ‘bursting’ and might play a key role in the particle transport processes in the
7 near-wall region. With more elaborate experiments, many recent studies supported this particle
8 entrainment mechanism based on the coherent structure (van Hout [22]; Baker & Coletti [5]). Thus,
9 understanding of the near-bed turbulence structure is essential to estimate the bed load transport and
10 to predict the development of the bed morphology (Nelson et al. [28]; Dey et al. [14]). Drake et al.
11 [15] reported that in a natural river flow, the sweep events frequently cause the collective motions
12 of sediment particles near a river bed. These investigations have shed light on the interaction
13 between coherent turbulence structure and particle transport. However, the particle transport
14 mechanism is not necessarily valid for sediment transport in natural gravel-bed rivers with complex
15 and random bed topography.

16 For rough-bed flow, most researches have investigated the interaction between the
17 turbulence structure over roughness elements and the transport process of a mobile particle of which
18 diameter is as large as the bed roughness (Dwivedi et al. [16]; Vowinkel et al. [51]; Ali & Dey [2];
19 Yousefi et al. [54]; Aleixo et al. [4]; Yücesan et al. [55]). Radice et al. [42] suggested that the
20 sediment particle motions are strongly correlated with the occurrences of sweep or ejection in the
21 mobile bed flow. Cameron et al. [9] indicated that single particles might be lifted up by the high-
22 momentum sweep motion when VLSM of turbulent flow overlays the particles. For quantitative
23 estimation, some previous studies tried to describe the intermittent behaviors of mobile particles by
24 stochastic methods (Liu et al. [25]; Pierce et al. [40]). However, considering the non-uniformity of
25 grain-size distribution in a natural riverbed, it is also essential to understand the fine particle
26 transport between and over coarse gravels. Papanicolaou et al. [39] pointed out the arrangement and
27 size of roughness elements changes the turbulence structure and the incipient motion of sediment
28 particles over rough bed. Ali & Dey [1] presented a novel model for the threshold of particle motion
29 over uniform and non-uniform riverbed, focusing on the drag and lift forces acting on a mobile
30 particle. Nevertheless, lack of information about the temporal and spatial scale of the bursting
31 phenomena between coarse gravels has prevented phenomenological understanding of the fine
32 sediment transport mechanism over rough bed based on the turbulence structure.

1 Although the turbulence structure over rough surface has received much attention for many
2 years, understanding of the rough bed flow has not been improved due to difficulties in velocity
3 measurement using PIV or laser Doppler velocimetry (LDV). Recently, a specific measurement set-
4 up called refractive-index matching (RIM) has been proposed to solve this problem in such optical
5 measurement techniques (Wiederseiner et al. [53]; Larsson et al. [24]). Generally, solid obstructions
6 in flow blind the flow field behind them in the field of view of camera since their refractive index
7 (RI) is different from that of surrounding fluid. The unmeasurable flow field within rough bed can
8 be visualized by matching RI of the solid body to that of the working fluid. Combining this method
9 with PIV, Kim et al. [23] conducted laboratory experiments where transparent acrylic spheres and
10 sodium iodide (NaI) solution were used as permeable walls and working fluid, respectively, to
11 measure flow field within rough bed. Some studies also devised an effective approach in which
12 super-absorbent polymer (SAP) is used as material for solid obstruction in aquatic flow (Byron &
13 Variano [7]; Weitzman et al. [52]; Harshani et al. [20]; Thaker et al. [49]). This method removes the
14 limitation of cost during experiment because ordinary water can be used as working fluid, while
15 preparing a large amount of NaI solution or other equivalent materials with high RI would be
16 impractically expensive. However, few studies have actually applied this transparent material to
17 velocity measurements in rough-wall flow; especially to investigation of the heterogeneous flow
18 structure and particle transport processes between roughness elements (Okamoto et al. [34]). To
19 explore the particle transport process, more information should be obtained using this visualizing
20 method: particle and fluid motion during particle lift-up; occurrence cycle and regions of
21 instantaneous upward flows within the rough bed; influence of turbulence structure on a particle's
22 step-length, for example. In this point, application of the SAP materials to velocity measurement
23 might be a breakthrough in exploring the fine particle entrainment between large-grain gravels.

24 The present study aims to provide an insight into the bursting phenomena and the
25 entrainment mechanism of a small mobile particle between and over roughness elements. To
26 consider the transport processes of a fine sediment particle over coarse gravels at rest in a natural
27 river, two kinds of laboratory experiments are performed for open-channel flow over fixed
28 hemispherical roughness elements. First, PIV is conducted to reveal the complex vortex structures
29 and the coherent motions of turbulent flow within and over the rough bed, which is likely to have
30 crucial impacts on particle transport process but has been little understood. Here, the RIM method
31 using SAP is adopted in the velocity measurement to enable visualization of the turbulence structure
32 in a valley of the rough bed. Next, motion of a single particle near the rough bed is investigated by

observing their trajectories. Particle trajectories and surrounding flow velocities are simultaneously measured to explore the relationship between particle motions and the coherent structure in turbulent flow. The structure of this paper is as follows: Section 2 describes the experimental set-up and methods for the PIV measurements and particle tracking experiments; Section 3 presents the PIV data to reveal the coherent structure within and around rough bed and the simultaneous analysis of turbulent flow and particle motions to discuss the particle entrainment mechanism; finally, the main findings of this study are summarized in Section 4.

2. Experimental Method

2.1 Experimental set-up

Figure 1a shows a schematic view of the experimental set-up and the coordinate system. The laboratory experiments were performed in a glass-made flume 10 m long, 0.40 m wide and 0.50 m high. In the present study, the x -, y - and z -axes correspond to the streamwise, vertical and spanwise coordinates, respectively. The origin of the coordinate system is located at the bottom ($y = 0$) and at the centerline ($z = 0$) of the channel. The corresponding components of instantaneous velocity, $(\tilde{u}, \tilde{v}, \tilde{w})$, are decomposed into the time-averaged components, (U, V, W) , and fluctuations, (u, v, w) , i.e., $\tilde{u} \equiv U + u$, $\tilde{v} \equiv V + v$ and $\tilde{w} = W + w$. The flow depth, H , was adjusted at $H = 12.0$ cm by a weir at the downstream end of the channel, which realized the uniform flow in the present experiments.

All experiments in this study were conducted for the flow over and within a rough bed. The rough wall was constructed by fixing hemispherical roughness elements with a diameter of $D = 3.6$ cm to the smooth bottom of the flume. The hemispherical shape of roughness elements expressed the riverbed topography where the top half of a large grain particle is exposed from the fine sediment occupying pores of the coarse gravels. Natural riverbed has a random topography because of the non-spherical shape of grains and non-uniformity in grain-size distribution. Nevertheless, since the complex features often make it difficult to deepen the understanding of the fundamental phenomena near a rough bed, many experimental researches simplified a natural gravel bed to spheres or hemispheres packed in a square array (Pokrajac & Manes [41]; Fang et al. [17]). However, this typical arrangement creates a spatially periodic flow structure in the spanwise direction since crests or valleys of roughness elements are aligned in the streamwise direction. To

balance the simplification of bed topography with the random features of a natural riverbed, the present study adopted a staggered array as an arrangement of roughness elements as shown in Fig 1b. The porosity of the rough bed ($y < D/2$) was geometrically estimated at 0.476, which is comparable to some previous laboratory experiments (Pokrajac & Manes [41]; Kim et al. [23]), numerical simulations (Bomminayun & Stoesser [6]; Fang et al. [17]) and field data for natural gravel-bed rivers (Darby [12]). The radius of the hemispherical roughness element corresponds to the roughness height ($k = D/2 = 1.8$ cm), and the relative submergence, $H/k = 6.7$, was classified as high relative submergence (Nikora et al. [31]), and comparable to those in some previous experimental studies investigating the large-scale turbulence structure over rough bed (Cameron et al. [8, 9]). The rough bed zone covered approximately 7 m in the streamwise direction.

2.2 Hydraulic conditions

Table 1 shows the hydraulic condition in the present study. The bulk mean velocity, U_m , and the relative submergence, H/k , were kept constant in all experiments ($U_m = 30$ cm/s; $H = 12.0$ cm). Reynolds number and Froude number are defined with the bulk mean velocity and flow depth, i.e., $Re \equiv U_m H / \nu$ and $Fr \equiv U_m / \sqrt{gH}$ (g : gravitational acceleration; ν : kinematic viscosity of water). Since the Froude number was much smaller than 1 and equivalent to that in PIV by Okamoto et al [36], free surface oscillation was negligible. Preliminary measurement by an ultrasonic wave gauge (sampling rate 10 Hz; measurement duration 60 s) also proved that the standard deviation of the free surface displacement was only 0.14% of the water depth. This indicates that the free surface oscillation is too small to disturb the LLS irradiated from above the channel, supporting adequacy of the velocity measurement. The friction velocity, u_* , was estimated by fitting the measured velocity profile to the logarithmic law, which will be described in more detail in Section 3.

2.3 PIV measurement

The two components of instantaneous velocity in the x - y plane, $(\tilde{u}, \tilde{v})$, were analyzed by PIV (Okamoto & Nezu [35]; Okamoto et al. [36, 37]). The test area was placed 4 m downstream of the leading edge of the rough bed region. Figure 2a shows the vertical distributions of the Reynolds shear stress at four streamwise positions ($x = 3$ m, 4 m and 5 m downstream of the leading edge of

the rough bed region) measured by PIV. At $x = 4$ m and 5 m, the value of the Reynolds stress is largest and there is little difference in the vertical distribution between the streamwise positions. This demonstrates that the flow is fully developed and almost uniform in the streamwise direction within $4 \text{ m} \leq x \leq 5 \text{ m}$, while turbulence is still developing at $x = 3$ m (1 m upstream of the test area). Contrary, the Reynolds stress might decrease in $x > 5$ m because the effects of the downstream flume end are not negligible. Thus, the region 4–5 m downstream of the leading edge of the rough bed region is found to be appropriate for the test area in PIV.

As fluid tracers, fine Nylon-12 particles with a diameter of $d_p = 80 \text{ }\mu\text{m}$ and a specific gravity of $\sigma/\rho = 1.02$ (σ : density of solid particles; ρ : density of water) were introduced to the water. Their Stokes number, defined as the ratio of the particle relaxation time, $\tau_p \equiv (\sigma/\rho)(d_p^2/18\nu) = 3.6 \times 10^{-4} \text{ s}$, to the smallest relevant time-scale of the flow, $\tau_* \equiv \nu/u_*^2 = 7.7 \times 10^{-4} \text{ s}$, was $St \equiv \tau_p/\tau_* = 0.47$, which implies the present seeding particles might not be fine enough to sensitively respond to the minimum-scale velocity fluctuation (Hjemfelt & Mockros [21]; Kim et al. [23]; Mollicone et al. [26]). On the other hand, the sampling time interval in the present velocity measurements ($\Delta t = 1/30 \text{ s}$ or $1/90 \text{ s}$, as described later) was much greater than the particle relaxation time ($\tau_p/\Delta t \approx 10^{-2}$). Therefore, the seeding particles were adequate enough for the present velocity measurement.

A laser light was continuously generated by a 3.0 W YAG laser source and converted into a 2.0 mm-thick laser light sheet (LLS) by a cylindrical lens. The LLS was vertically projected into flow around the test area from the free surface. The spanwise position of LLS was at the center of the flume ($z/k = 0$), including crests and valleys of roughness. The flow pictures visualized by the illuminated tracers in the x - y plane were taken using a high-speed camera (HAS-EF, Ditect) which is controlled by a personal computer and connected to a pulse signal generator. The resolution of the recorded images was $1,280 \times 1,024$ pixels (approximately $20 \text{ cm} \times 15 \text{ cm}$ in real scale) and the frame rate of the camera was 500 Hz.

The settings for PIV were similar to Okamoto & Nezu [35] and Okamoto et al. [36], aiming to investigate the large-scale turbulence structure with flow depth scale over the macro-rough bed. Velocity data were analyzed using Flownizer2D software (Ditect) based on the direct cross-correlation method: to calculate the particle displacement between two consecutive images, an interrogation window was set in the first frame and a search region, the area of interest for calculating the cross-correlation with the interrogation window, at the second frame. The size of an interrogation window was 27×27 pixels (about $3.7 \text{ mm} \times 3.7 \text{ mm}$). The time interval of $1/500 \text{ s}$

between consecutive images resulted in the maximum seeding particle displacement of approximately 5 pixels for the present hydraulic condition ($U_m = 30$ cm/s). On the other hand, the temporal resolution of the camera was much higher than that required to measure the large-scale turbulence structure targeted in this study ($\approx H/U_m = 0.4$ s), and would shorten the measurement duration due to the limitation of built-in camera memory. Hence, A pulse signal generator was connected to the camera, and extracted a pair of images (with the interval of 1/500 s) with a sampling rate of 30 Hz as described in Fig 1c (Nezu & Sanjou [30]; Okamoto et al. [36, 37]). The number of the image pairs was 1,800, and the measurement duration was 60 s. Figure 2b presents four samples of the Reynolds stress distribution obtained by 60 s, 120 s, 180 s and 240 s long PIV measurements. This demonstrates that 60 s was long enough to obtain reliable data because there is little variation in the measurement data with the measurement duration.

To visualize the flow field behind roughness by RIM, around the measurement area, roughness elements between the camera and the LLS were made from super-absorbent polymer (SAP). As shown in Fig 1b, the non-transparent hemispheres in a single spanwise row were replaced with the transparent ones, which expanded a field of view of the camera. The SAP can swell to several hundred times in volume by absorbing water and become a transparent gel called ‘hydrogel’ (Wiederseiner et al. [53]; Weitzman et al. [52]). Since the RI of the gel is almost equivalent to that of water ($RI = 1.33$), the transparent obstructions did not block the fields of view of the camera and allowed us to observe inside the roughness layer (Byron & Variano [7]). To produce a transparent sphere made from hydrogel, a dried, spherical particle of SAP (about 5 mm in diameter) was put in a spherical mold (3.6 cm in diameter) filled with water for two days. After that, each of the hydrogel balls was cut into two hemispherical roughness elements with the same shape as the non-transparent roughness elements. It was not observed during the experiments that the hydrogel swelled due to water absorption since time durations of all the measurements were short enough. Moreover, any effects of deformation and vibration of the transparent roughness elements on the values of flow velocity seemed to be negligible. This point will be discussed later.

2.4 Particle-tracking experiment

The particle-tracking experiment consists of two types of measurements. First, measurements of some particle trajectories over the rough bed were conducted to roughly observe particle motions in a horizontal plane as preliminary experiments. Second, the simultaneous

measurement of the particle trajectories and the surrounding flow velocity was performed for a considerable number of entrainment events between roughness elements to investigate the relationship between the bursting phenomena and particle entrainment. In this experiment, the velocity data was obtained by PIV while particle motions were tracked on recorded images for PIV. The present study focused on the influences of the coherent structure on particle transport; therefore, the number of particles introduced to flow were small enough to neglect effects of particle existence on turbulence or collision of mobile particles.

As mobile particles, we used natural plant seeds with almost spherical shape (broccoli seeds) with a diameter of $d_p = 0.19$ cm and a specific gravity of $\sigma/\rho = 1.21$. The seed particles were soaked for 24 hours before measurements to stabilize their physical characteristics. Table 2 shows some physical properties of the mobile particle. For reference, the non-dimensional diameter, $d_p^+ \equiv d_p u_* / \nu$, and the Shields number, $Sh \equiv u_*^2 / \{(\sigma/\rho - 1)g d_p\}$, are also shown. The reason why the particle was employed as a mobile particle is their behaviors were observed to be intermittent under the present hydraulic condition, which is suitable to understand the particle entrainment mechanism. The particle parameters (V_t/u_* and d_p^+) were of the same order as those in some previous studies (Sumer & Deigaard [46]; van Hout [22]; Tee et al. [48]; Baker & Coletti [5]). In considering the vertical transport process of particles with a specific gravity greater than water ($\sigma/\rho > 1$), the particle relaxation time is often defined as $\tau_p \equiv (\sigma/\rho - 1)(d_p^2/18\nu)$ to account for the effect of gravity. Adopting this definition, the Stokes number of the mobile particle is estimated at $St = 55$ and is of the same order as that in previous investigations (van Hout [22]; Baker & Coletti [5]). The settling velocity measured in still water was $V_t = 5.2$ cm/s, which is equivalent to that of a sand particle with a diameter of 0.39 mm ($St = 18$). Hence, the vertical transport mechanisms of the seed particle used in this study and the equivalent sand particle are expected to be similar although there may be some differences in sensitivity to ambient velocity fluctuations due to the differences in Stokes number.

In the rough observation of particle trajectories, particle motions in a horizontal plane, $(x_p(t), z_p(t))$, were recorded from top using a video camera. The particle centroid positions were manually tracked on the consecutive recorded images using an image processing software MTrackJ (Meijering et al. [27]). Before each measurement, about five particles were introduced into the flow from the upstream flume end, having no significant influence on the flow structure. The sampling rate of images was 10 Hz, which ensures sufficient time-resolution to track the relatively large-scale particle motion. The total sampling time was 20 minutes in each experiment. Observation window

size was 1920×1080 pixels, covering an area of $63 \text{ cm} \times 35 \text{ cm}$.

The simultaneous measurement of flow and particle velocities was conducted in the experimental set-up as shown in Fig 1d. For the observation of particle trajectories by a video camera, five seeding particles were added from the upstream flume end before starting measurement. Some entrainment events of a particle in LLS between roughness elements were detected in the recorded images for PIV, and their trajectory data, $(x_p(t), y_p(t))$, were obtained by MtrackJ. Repeating the measurement procedures enabled us to obtain 184 entrainment events. The data sampling rate of PIV was set at 90 Hz to conduct more temporally resolved analysis than the flow velocity measurement described in the previous subsection. The sampling rate of 90 Hz was high enough to detect the turbulence structure affecting the particle motion because the particle relaxation time ($\tau_p = 0.24 \text{ s}$) was much longer than $1/90 = 0.011 \text{ s}$. The number of sampled image pairs was 1,800 as well, so that the measurement time was 20 s for each measurement. Since the number of particles was extremely small as mentioned above, there was no significant difference in PIV results of the time-averaged velocities and turbulence statistics between the fluid-only and the particle-laden cases.

3. Results

3.1 Mean flow structure

First of all, applicability of the SAP hydrogel to the RIM-PIV measurement needs to be verified. Since the hydrogel is more flexible than the non-transparent roughness elements made from rubber, replacing the rigid hemispheres by the transparent ones might have some influences on surrounding flow field due to their vibration and deflection. Prior to all the PIV experiments, preliminary velocity measurements were performed for two vertical planes: one includes a crest of the non-transparent hemisphere ($z/k = 1$) and the other of the transparent one ($z/k = -1$). Figure 3 compares the mean flow velocity distributions in the two vertical planes: (a, b) the streamwise component, U , and (d, e) the vertical one, V . The dark-gray areas and the white ones in the contours correspond to roughness elements in LLS and unmeasured regions in a valley where the roughness hemispheres in the front blocks the field of view, respectively. Comparison between the velocity distributions around the non-transparent roughness element, (U_N, V_N) , and the transparent one, (U_T, V_T) , demonstrates there is no significant difference between the roughness types (Fig 3c, 3f),

which means the roughness flexibility has little effect on the flow field. In addition, no vibration and deflection of the hydrogel were visually observed during the experiments. Therefore, it is clear that this visualizing method using the transparent roughness elements is applicable to PIV in the present work.

Figure 4a shows a color contour of the mean flow velocity around the rough bed, U . The black vectors denote the mean flow velocities, (U, V) . The flow structure in the valley between roughness elements, surrounded by the white dashed line, was visualized successfully using the transparent hydrogel. In the roughness sublayer ($y/k < 1.2$), the bed surface creates a complex flow field, while the velocity distribution in the log-law layer is roughly uniform in the streamwise direction. The drag force by roughness reduces flow velocity near the rough bed and generates a shear layer around the roughness height ($y/k \approx 1$). The velocity shear, $\partial U/\partial y$, is strongest just behind the roughness element ($1.5 < x/k < 2.5$), which is because of flow separation.

The friction velocity was estimated from the measured vertical profile of the spatially averaged mean flow velocity, $\langle U \rangle(y)$. Since the mean flow structure is spatially periodic due to the bed topography, the double-averaged velocities (Nikora et al. [31]) can be defined as follows:

$$\langle U \rangle(y) \equiv \frac{1}{4k \cdot \phi(y)} \int_k^{5k} U(x, y) dx \quad (1)$$

Here, $4k \cdot \phi(y)$ is the total streamwise length of the pores between the roughness elements at each elevation. In the spatial average operation, we considered only the pores where roughness elements did not exist. Since the roughness elements were hemispheres and their sizes were uniform, the function is obtained geometrically as follows:

$$\phi(y) \equiv \begin{cases} 1 & (y \geq k) \\ 1 - \sqrt{1 - (y/k)^2} & (0 < y < k) \end{cases} \quad (2)$$

The logarithmic law in an open-channel flow over rough bed is expressed as

$$\frac{\langle U \rangle(y)}{u_*} = \frac{1}{\kappa} \ln \left(\frac{y - y_0}{k} \right) + B \quad (3)$$

where y_0 denotes the virtual origin of the log-law and B is a constant (Raupach et al. [44]; Fang et al. [17]). The von Karman constant, κ , is assumed to be $\kappa = 0.41$. By fitting the log-law distribution to the measured velocity profile, the parameters in Eq. (3) were estimated: $u_* = 3.6$ cm/s, $y_0/k = 0.83$ and $B = 7.4$. Figure 4b shows the vertical profile of the double-averaged flow velocities. Here, the black line denotes the fitted log-law distribution. The measurement values are in good agreement with Eq. (3) in the region of $1.2 \leq y/k \leq 2.4$ ($0.18 \leq y/H \leq 0.35$), which is defined as the log-law layer. On the other hand, the log-law does not hold around the roughness ($y/k < 1.2$), and this region corresponds to the roughness sublayer (Nikora et al. [31]).

1 A contour map of the mean vertical flow velocity, V , is shown in Figure 4c. As well as the
2 streamwise components, spatial change in the flow structure is significant in the roughness sublayer,
3 but negligible in the log-law layer. Around every roughness crest ($x/k \approx 1$ and 5 ; $y/k \approx 1$), a pair
4 of upward and downward flows are formed along the roughness surface. Below the roughness
5 height ($y/k < 1$), there are also several upward and downward flows between the roughness
6 elements ($2 < x/k < 4$). In the enlarged view, it is observed that a vortex-shaped flow is formed in
7 the downstream side of the valley ($3.4 < x/k < 4.1$; $y/k < 0.6$). This suggests that in this region, a
8 flow collides with the roughness and the flow direction is changed to the downward direction along
9 the roughness surface, which resembles the horseshoe vortex generated around a solid obstruction
10 such as a bridge pier.

11 3.2 Turbulence characteristics and coherent structure

12 Figure 5 shows the Reynolds shear stress distribution, $-\overline{uv}$: (a) vertical distributions at
13 $x/k = 1.0$ – 4.5 and (b) color contour map in the vertical plane. To improve visibility, the values of
14 $-\overline{uv}/U_m^2$ in Fig 5a are shown shifted by 0.01 for each streamwise position. All the streamwise
15 positions have the almost linear profiles apart from the rough bed ($y/k > 1.5$), and the distributions
16 have peak values around the roughness height ($y/k \approx 1$), which is the typical shape of the shear
17 stress distribution for open-channel flows (Pokrajac & Manes [41]; Fang et al. [17]). In addition, the
18 linearity of the Reynolds stress distributions, as well as the logarithmic velocity profile, indicates
19 the full development of the flow around the measurement section. The contour plot (Fig 5b) also
20 indicates the momentum transport by turbulence is most intensive just behind a roughness crest (1.5
21 $< x/k < 3.0$; $y/k \approx 1$). This region corresponds to the local, strong shear layer formed by the flow
22 separation from the roughness surface demonstrated in Fig 4a. Therefore, the large velocity
23 difference above and below the roughness height generates vortices in the local shear region by the
24 Kelvin-Helmholtz instability. In the downstream region of the valley ($3 < x/k < 4$), the peak
25 values of Reynolds stress decrease in the streamwise direction, while the shear layer with
26 significant Reynolds stress ($-\overline{uv}$) expands close to the channel bed. This means that the vortices
27 generated in the shear layer transport fluid momentum into the vicinity of the bottom ($y/k \approx 0$).
28 Contrary, there is a region with negative Reynolds stress along the upstream surface of a roughness
29 element ($4.1 < x/k < 5.0$). This indicates that drag force by the roughness may weaken the
30 instantaneous fluid motion perpendicular to the hemispherical surface ($u < 0$ and $v > 0$; $u > 0$ and

$v < 0$) and change the flow direction ($u > 0$ and $v > 0$; $u < 0$ and $v < 0$).

To explore the turbulent transport process of fluid momentum in more detail, the quadrant analysis is conducted for the instantaneous Reynolds shear stress, $-u(t)v(t)$. In this analysis, the velocity fluctuations, (u, v) , are classified into the four quadrant events (Raupach et al. [44]; Bomminayun & Stoesser [6]): the first quadrant with $u > 0$ and $v > 0$ (outward interaction); the second quadrant with $u < 0$ and $v > 0$ (ejection); the third quadrant with $u < 0$ and $v < 0$ (inward interaction); the fourth quadrant with $u > 0$ and $v < 0$ (sweep). Then, the i -th quadrant Reynolds stress, RS_i , ($i = 1, 2, 3, 4$) is expressed as

$$RS_i = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \{-u(t)v(t)\} \cdot I_i(t) dt \quad (4)$$

where $I_i(t)$ is a discriminant function: if (u, v) exists in the i -th quadrant, $I_i(t) = 1$; otherwise, $I_i(t) = 0$. Figure 6 presents the vertical distributions of the quadrant Reynolds shear stress at $x/k = 1.5, 2.5, 3.5$ and 4.5 . Over the rough bed ($y/k > 1$), contributions of ejections, RS_2 , and sweeps, RS_4 , are much greater than those of the other events (RS_1 and RS_3). Around and below the roughness height ($y/k < 1.2$), the high-momentum flow with downward motion is more effective in momentum transport than the upward low-momentum flow. The similar tendency was reported in previous studies on fully developed vegetation-canopy flows (for example, Okamoto & Nezu [35]). Therefore, within the roughness sublayer, the sweep (RS_4) plays a more important role in turbulent transport process than the ejection (RS_2).

To investigate the relationship between the coherent structures below and above the roughness height, linear stochastic estimation (LSE) is performed for the flow field around the rough bed. The LSE analysis is an application of correlation analysis and used to estimate the conditional flow field given a certain event (Tomkins & Adrian [50]; Coceal et al. [11]). In this study, an upward flow event ($v > 0$) at a fixed reference point, (x_0, y_0) , was chosen as a specific event to explore the effect of the bursting phenomena on the particle entrainment between roughness elements. Here, two reference points are selected: $(x_0, y_0) = (3.5k, 0.25k)$ (near the channel bottom) and $(x_0, y_0) = (3.5k, 1.0k)$ (at the roughness height). The LSE of the conditional flow field, $\hat{u}_i(x, y, t + \Delta\tau)$, can be expressed as follows:

$$\hat{u}_i(x, y, t + \Delta\tau) = A_{u_i v}(x, y, \Delta\tau)v(x_0, y_0, t) \quad (5)$$

Here, $\Delta\tau$ is the time lag between the conditional flow field at (x, y) and the vertical flow velocity at (x_0, y_0) . The coefficient in the right side, $A_{u_i v}$, can be estimated as:

$$A_{u_i v}(x, y, \Delta\tau) = \frac{\overline{\{u_i(x, y, t + \Delta\tau)v(x_0, y_0, t)\}}}{\overline{\{v^2(x_0, y_0, t)\}}} \quad (6)$$

Figure 7a shows the conditional streamwise flow fields given an upward flow event at $(x_0, y_0) = (3.5k, 0.25k)$ with the time lag of $\Delta\tau = -0.20$ s, -0.10 s and 0 . The variation of the conditional flow field with $\Delta\tau$ captures a typical mechanism for the occurrence of an upward flow between roughness elements. Before the occurrence of the upward flow near the channel bed ($\Delta\tau = -0.20$ s), a high-momentum flow ($u > 0$) passes over the roughness height ($x/k > 4$; $1 < y/k < 2$), and sweep ($u > 0$; $v < 0$) penetrates between roughness elements. After that ($\Delta\tau = -0.10$ s and 0), the sweep impinges on the roughness element, and then generates a significant upward flow near the channel bed by enhancing the horseshoe vortex ($3 < x/k < 4$; $y/k < 1$). These observations demonstrate that the passage of a large-scale high-speed flow ($u > 0$) over the roughness height may result in the prominent upward flow in the near-bed region. Figure 7b presents the variation of the coefficient $A_{u|v}$ at $(x, y) = (3.5k, 1.0k)$ with the time lag, $\Delta\tau$. The coefficient $A_{u|v}$ is positive before and after the occurrence of the near-bed upward flow ($-0.8 \text{ s} \leq \Delta\tau \leq -0.1 \text{ s}$; $0.1 \text{ s} \leq \Delta\tau \leq 0.9 \text{ s}$) and has a peak value at $\Delta\tau = -0.23$ s. However, $A_{u|v}$ is rapidly decreases to zero around $\Delta\tau = 0$, suggesting the lack of sweep during the occurrence of the upward flow. This means that the near-bed upward flow occurs after the high-momentum flow passes over the roughness height or when a short break of the high-speed region exists over the valley of the rough bed. Figure 7c shows the conditional streamwise flow field given an upward flow at $(x_0, y_0) = (3.5k, 1.0k)$ with $\Delta\tau = 0$. In contrast to the near-bed upward flow event (Fig 7a), the contour shows negative values around the reference point, indicating the occurrence of ejection ($u < 0$; $v > 0$). Thus, the upward flows near the channel bottom and around the roughness height are generated by the quite different mechanisms connected with the coherent structures.

Figure 8a shows the time variation in the vertical distribution of the streamwise velocity fluctuations, $u(t, y)$, at $x/k = 3.5$. The white and dark-gray regions correspond to high-momentum flows ($u > 0.1U_m$) and low-momentum flows ($u < -0.1U_m$), respectively. It is observed that the high- and low-momentum regions pass through alternately over the roughness height ($1 < y/k < 5$). In this 15 s long time-series, 3 to 4 pairs of the prominent high- and low-momentum flows are identified (occurrence period $T \approx 4$ s; $TU_m/H \approx 10$). Figure 8b shows the time-series of the vertical distribution of the vertical velocity fluctuations at $x/k = 3.5$, $v(t, y)$. This figure suggests that sweeps ($u > 0$; $v < 0$) and ejections ($u < 0$; $v > 0$) occur intermittently during the passage of high- ($u > 0$) and low-momentum flows ($u < 0$), respectively. Figure 8c shows the time-series data of the instantaneous vertical flow velocities, $\tilde{v}(t)$, near the channel bottom ($x/k = 3.5$; $y/k = 0.25$) for the same time period as Figs 8a and 8b. Here, the significant upward flow events are defined as

1 the upward flow with $v > \sqrt{v^2}$ (indicated by the red or blue ellipses). The greater part of the
2 significant upward flows (indicated by red ellipses) occurs during the passage of the high
3 momentum flow ($u > 0$), which coincides with the intermittent occurrence of sweeps around the
4 roughness height shown in Fig 8b. This suggests that the generation mechanism of the strong
5 upward flow in the near-bed region relates to the large-scale coherent structure over the rough bed,
6 as demonstrated in Fig 7a. Figure 8d presents some examples of the upward flow regions caused by
7 the collision of sweep with roughness surface shown in Fig 8c. The red areas indicate the regions
8 with $\tilde{v} > 0.1U_m$ at the moments shown by the red arrows (1–5) and (8) in Figs 8a and 8b. There is
9 some variation in the size of the upward flow regions and their upper limits range within $0.5 \leq$
10 $y/k \leq 1.5$.

11 3.3 Particle entrainment between roughness elements

12 In this subsection, results of the simultaneous analysis of flow and particle motion will be
13 demonstrated to explore the relationship between the turbulence structure and the particle
14 entrainment. Figure 9 shows a trajectory of a single particle transported within and over the
15 roughness elements: (a) the trajectory in a horizontal plane, (x_p, z_p) ; (b) the time-series of the
16 streamwise particle centroid positions, $x_p(t)$. It is observed that the particle was trapped between
17 roughness elements and ejected again from the rough bed. Here, a motion of a particle from the
18 time it starts to move in the streamwise or spanwise directions until it stops again in the rough bed
19 is regarded as a single step of the particle behavior. The trajectory shown in Fig 9a consists of six
20 steps (step-length $L = D, 0, 5D, 3D, 0$ and 0), which can be roughly classified into two types of
21 particle behavior. One is a shorter step in which a particle moves in streamwise or spanwise
22 directions while passing through roughness elements. The step-lengths of such a short motion are
23 almost equal to one diameter of the roughness hemisphere or less ($L \leq D$). The other is a longer
24 step ($L > D$) in which a particle is transported over the roughness height ($y > k$). The difference
25 between the two behaviors may be attributed to the coherent structure of turbulent flows. Moreover,
26 Fig 9b suggests the waiting time between roughness elements, t_w , varies widely from step to step.
27 This random behavior also implies the initiation of a particle step might depend on the intermittent
28 flow motion near the rough bed.

29 Figure 10 shows an example of the particle trajectories observed in the experiment. The
30 time-series data of the vertical particle position, $y_p(t)$, (Fig 10a) includes two entrainment events

1 between roughness elements, of which trajectories in a vertical plane are shown in Fig 10b. During
 2 the first event ('1st lift-up'), the particle is lifted up to $y_p/k = 0.7$ ($-2.2 \text{ s} < t < -1.7 \text{ s}$) and then
 3 falls down to the bottom ($-1.7 \text{ s} < t < -0.9 \text{ s}$). On the other hand, the second entrainment ('2nd lift-
 4 up'; $t > 0 \text{ s}$) is an upward motion that started from the bottom ($y = 0$) and persists even above the
 5 roughness height ($y_p > k$). Fig 10c presents the time series of the instantaneous vertical velocities,
 6 $\tilde{v}(t)$, at $y/k = 0.25$ and 0.50 (near the channel bottom) and the instantaneous velocity fluctuations,
 7 $u(t)$ and $v(t)$, at $y/k = 1.0$ ($x/k = 3.5$). For clarity, the values for the two heights ($y/k = 0.5$ and
 8 1.0) are shifted by 1. At the roughness height ($y/k = 1.0$), a significant velocity fluctuation with
 9 $u > 0$ and $v < 0$ is observed just before each particle lift-up ($-2.5 \text{ s} < t < -2.2 \text{ s}$; $-0.6 \text{ s} < t < -0.1$
 10 s). This demonstrates that the sweep ($u > 0$; $v < 0$) occurs around and penetrates into the rough
 11 bed. After that, the vertical flow velocity near the bottom ($y/k = 0.25$ and 0.5) becomes
 12 significantly positive while the particle is moving up ($-2.2 \text{ s} < t < -2.0 \text{ s}$; $-0.1 \text{ s} < t < 0.4 \text{ s}$), which
 13 seems induced by the sweep as implied in Fig 7. In addition, the duration of the upward flow in
 14 '2nd lift-up' is longer than that in '1st lift-up'. This might make the difference in the termination
 15 heights of upward path between the two events.

16 Figure 11 presents the sequences of contour maps of (a) the streamwise velocity
 17 fluctuations, u , and (b) the instantaneous vertical velocities, $\tilde{v}$, for the '1st lift-up' event in Fig 10,
 18 in which the particle stays in the valley of the rough bed at last. First, a sweep ($u > 0$; $v < 0$)
 19 generated above the rough bed collided with the downstream roughness element ($y/k \approx 1$; $t = -$
 20 2.20 s), and then the instantaneous upward flow occurred around the particle ($3 < x/k < 4$; $0 <$
 21 $y/k < 1.2$; $t = -2.10 \text{ s}$). The particle trajectory and centroid position at each instant shown in the
 22 color contours demonstrate that a mobile particle is lifted up by the instantaneous flow event
 23 induced by the penetration of sweep. Since the upward flows in roughness valleys are enhanced by
 24 the downward transport of high momentum (Fig 7), the fine particle resuspension between large bed
 25 particles is likely to occur intensively during passage of the high-momentum regions ($u > 0$). After
 26 the particle lift-up ($t = -1.60 \text{ s}$), the enhanced upward flow surrounding the particle became weakened,
 27 which resulted in the downward particle motion due to gravity. Thus, the variance of duration and
 28 range of the instantaneous upward flows within rough bed, suggested in Fig 8c, might determine the
 29 termination height of an upward particle path.

30 As for the '2nd lift-up' event in which the particle is flown to outside of the rough bed,
 31 Figure 12a, b shows temporal variation of the instantaneous flow field in the same way as Fig 11.
 32 Figure 12c demonstrates time series of the vertical distributions of the streamwise velocity

fluctuations, u , and the instantaneous vertical velocities, $\tilde{v}$, at the streamwise particle position at each moment ($x = x_p(t)$): $u(x_p(t), y)$ and $\tilde{v}(x_p(t), y)$. Here, the black lines denote the vertical particle positions, $y_p(t)$. As described for the first event (Fig 11), a high-momentum flow penetrated into the rough bed ($u > 0$; $v < 0$) and generated a prominent upward flow between roughness elements, which blew up the particle staying on the bottoms ($-0.6 \text{ s} < t < 0.0 \text{ s}$). In this event, some instantaneous upward flows occurred intermittently around the ascending particle, and especially ejections ($u < 0$; $v > 0$) were generated around the particle lifted up to about the roughness height ($t = 0.20 \text{ s}$). These observations indicate that the upward flow induced by sweep may be a trigger of the particle entrainment between roughness elements, and that a following ejection may raise and transport the particle over the rough bed ($y/k > 0.5$). In smooth-wall flows, ejections cause the particle resuspension from the vicinity of the wall (Sumer & Ögüz [47]; Niño & García [33]; van Hout [22]) and play a crucial role in particle entrainment processes rather than sweeps (Baker & Coletti [5]). Thus, the existence of roughness enhances the importance of the fourth quadrant events in fine sediment transport within and over rough bed.

As demonstrated in Fig 7b, the upward flow near the channel bottom occurs roughly 0.2 s after the collision of sweep with a roughness element. To estimate the proportion of the entrainment events triggered by sweep, all detected entrainment events were classified based on the turbulent events around the roughness height 0.1–0.3 s before the initiation of each entrainment event. Here, the velocity data just before particle entrainment ($t_E - 0.3 \text{ s} \leq t \leq t_E - 0.1 \text{ s}$, where t_E is the start time for each entrainment event) were available for only 167 events out of the 184 events detected in the recorded images. First, for each event, the streamwise flow velocity temporally averaged for $t_E - 0.3 \text{ s} \leq t \leq t_E - 0.1 \text{ s}$, $\bar{u}_{BE}$, was calculated to determine whether high- ($\bar{u}_{BE} > U$) or low-momentum flow ($\bar{u}_{BE} < U$) passed around the roughness height:

$$\bar{u}_{BE} = \frac{1}{\Delta\tau_2 - \Delta\tau_1} \int_{t_E + \Delta\tau_1}^{t_E + \Delta\tau_2} \tilde{u}(t) dt \quad (\Delta\tau_1 = -0.3 \text{ s}; \Delta\tau_2 = -0.1 \text{ s}) \quad (7)$$

Here, two points around the roughness height are considered as a reference point for velocity data: $(x, y) = (3.5k, 1.0k)$ and $(x, y) = (3.5k, 1.5k)$. Next, the occurrences of sweep (Q4 event: $u > 0$; $v < 0$) and ejection (Q2 event: $u < 0$, $v > 0$) were examined for the entrainment events after high-momentum flow passage and those after low-momentum flow passage, respectively. In detecting the Q2 and Q4 events, a threshold value for $-uv$ was used to exclude weak coherent structures as follows:

$$-uv > H|\overline{uv}| \quad (8)$$

Here, H is a threshold level so-called ‘hole value’ (Nezu & Nakagawa [29]) and is set at $H = 1$.

Table 3 shows that more than 70% of the entrainment events occurred just after the passage of sweep and that the entrainment events after ejection or other events account for only less than 30%. This demonstrates the particle entrainment mechanisms between roughness elements are strongly connected with the upward flow induced by the collision of sweep, as observed in Figs 11 and 12.

Figure 13a shows the probability distribution of the termination height of an upward path from the channel bottom, y_{end} , for the 184 entrainment events. In this figure, 94.6% of the detected trajectories ended below the roughness height ($y_{\text{end}} < k$), and 58.7% terminated in $y < 0.4k$ (the mean termination height $\bar{y}_{\text{end}}/k = 0.44$). This suggests that most particles lifted up from the channel bottom do not reach the outer flow ($y > k$) but fall back to the bottom or move in the spanwise direction between roughness elements, such as the 1st lift-up in Fig 11. Contrary, the number of particles directly transported to the outer flow was limited to 5.4% of the total entrainment events, including the 2nd lift-up (Fig 12). Figure 13b shows the probability distribution of y_{end} only for the 118 entrainment events triggered by sweep at $(x, y) = (3.5k, 1.0k)$ (shown in Table 3), which does not differ markedly from that for the total events (Fig 13a). This suggests even the upward particle motions induced by sweep can be transported beyond the roughness height ($y > k$). However, the maximum value of y_{end} is $y_{\text{end}} \approx 1.5k$ and much higher than the upper limit of the upward flow by the horseshoe vortex as shown in Fig 4c ($y/k \approx 0.6$). Thus, the process of the particle lift-up into the outer flow ($y/k > 1$) might be based on a different mechanism from the lift-up near the channel bottom.

Figure 14 shows the sequence of the instantaneous flow fields and the centroid positions of a particle that moves down and then stops on the channel bed. The trajectory of the falling particle and the instantaneous velocity fields suggest that sweeps transported the particle downward at $t = -0.60$ s and resulted in the particle transport into the rough bed at $t = 0$ s. However, the downward motion was just slowed but not turned into an upward motion even at $t = -0.40$ s and -0.20 s, when the ejection occurs around the particle. This is because the specific gravity of the particle is greater than one and thus the particle can fall down unless any sufficient upward flows occur around it even if an instantaneous downward flow does not exist.

3.4 Particle transport processes in rough-bed flow

Figure 15 illustrates the particle transport mechanisms based on the bursting phenomena over the rough bed. The initiation of particle motion between roughness elements is predominantly

induced by the passage of a high-momentum flow ($u > 0$) over the roughness height (more than 70% of the total entrainment events). Just after the high-momentum flow passes (Fig 15a), the collision of sweep with a roughness element ($u > 0; v < 0$) enhances the horseshoe vortex and thereby generates a significant upward flow near the channel bed. This instantaneous upward flow lifts up a particle from the channel bottom to $y/k = 0.44$ on average (Fig 15b). Then, if a strong ejection event ($u < 0; v > 0$) occurs around the roughness height ($y/k \approx 1$), the particle lifted up by sweep continues to move up across the roughness height ($y > k$) and is transported over a long distance in the streamwise direction until the ejection breaks up or the particle drops out of the low-momentum flow due to gravity (Fig 15c). Otherwise, the suspended particle starts to fall back to the channel bottom ($y = 0$), or to travel over a short distance in the spanwise or streamwise directions by drifting between roughness elements ($L \leq D$) since there is no sufficient upward flow to lift up the particle or the next sweep event comes from upstream (Fig 15d).

The particle entrainment mechanism based on the passage of sweep covers more than 70% of the detected entrainment events, but entrainment mechanisms for the other events have not been revealed yet. Since this study performed the velocity measurement only for one vertical plane, the spanwise evolution of the coherent structures and its effects on particle motion should be investigated as well. Coceal et al. [11] suggests the vortex structure that develops over macro-rough bed is non-uniform in the spanwise direction. Hence, it is necessary to understand the three-dimensionality of the coherent structures over the rough bed.

4. Conclusions

The present study explored the coherent structure of turbulent flows and its influences on particle transport from rough bed by PIV and the particle-tracking experiment. In the PIV measurement, an effective experimental method called RIM was also introduced, offering some valuable information on the unrevealed flow structure in a valley of the rough bed and entrainment of a fine particle laid between roughness elements. Results of the velocity measurement and particle-tracking elucidated a phenomenological model for the particle entrainment based on the coherent turbulence structure over a macro-rough bed. The key findings are as follows:

1. Using the transparent material with low refractive-index (SAP) as roughness elements, the complex flow field in the valley region was successfully measured in PIV. In the roughness

sublayer ($y/k < 1.2$), the topography of the rough bed creates a non-uniform flow structure in the streamwise and spanwise directions. The horseshoe vortex is formed along the upstream side of a roughness element, which might cause suspended particles to be transported to the inside of rough bed or lifted up from the bottom.

2. Over the roughness height ($y/k > 1$), there is a large-scale cyclic motion of the streamwise velocity fluctuations consisting of the high- and low-momentum flows (frequency $TU_m/H \approx 10$), which plays an important role in the momentum transport by ejection ($u < 0; v > 0$) and sweep ($u > 0; v < 0$). The LSE analysis demonstrates that a strong upward flow is generated near the channel bottom approximately 0.2 s after a high-momentum flow passed over the roughness height, and that a sweep collides with a roughness element. In contrast, the upward flow around the roughness height is predominantly connected with the occurrence of ejections.

3. The simultaneous analysis of the instantaneous flow fields and the particle trajectories suggests the strong connection between the large-scale coherent structure over rough bed and the particle entrainment mechanisms between roughness elements. The strong upward flow induced by sweep triggers the particle lift-up from the near-bed region ($y_{\text{end}}/k \approx 0.44$ on average). This entrainment mechanism based on the passage of sweep covers more than 70% of the observed entrainment events.

4. Most particle motions that start near the channel bottom terminate below the roughness height ($y_{\text{end}}/k < 1$), and thus a particle is often transported for a short distance in the streamwise or spanwise direction between roughness elements. On the other hand, a few particles (about 5% of the total entrainment events) are lifted to the outer flow ($y_{\text{end}}/k > 1$) and then transported for a long distance in the streamwise direction. This difference in the particle behavior depends on whether an ejection occurs around a particle raised from the near-bed region.

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28 **Notations**

29 $A_{u_i v}$ LSE coefficient

1	B	constant in the log-law for the rough-wall flow
2	D	diameter of the roughness element
3	d_p	diameter of the suspended particles
4	d_p^+	non-dimensional diameter of the suspended particles ($= d_p u_* / \nu$)
5	Fr	Froude number ($= U_m / (gH)^{1/2}$)
6	g	gravitational acceleration
7	H	flow depth
8	k	roughness height
9	L	step length for a single motion of a particle
10	n	sample size of step-length and waiting time
11	Re	Reynolds number ($= HU_m / \nu$)
12	Sh	Shields number ($= u_*^2 / \{(\sigma / \rho - 1)g d_p\}$)
13	St	Stokes number ($= \tau_p / \tau_*$)
14	T	period of cyclic flow motions
15	t_w	waiting time for a single motion of a particle
16	u_*	friction velocity of flow
17	$\bar{u}_{BE}$	streamwise velocity just before an entrainment event
18	U_m	bulk mean velocity
19	U_{Q2}, U_{Q4}	conditional averaged velocity given ejection and sweep, respectively
20	(U, V, W)	mean flow velocity
21	(u, v, w)	flow velocity fluctuation
22	$(\tilde{u}, \tilde{v}, \tilde{w})$	instantaneous fluid velocity in (x, y, z)
23	$\hat{u}, \hat{v}$	conditional flow velocity estimated by LSE
24	u'_{pf}, v'_{pf}	velocity difference between particle and mean flow
25	V_t	settling velocity of the suspended particles
26	(x, y, z)	streamwise, vertical and spanwise coordinates
27	(x_p, y_p, z_p)	position of particle centroid
28	y_{end}	vertical position at termination of upward motion of a particle
29	y_0	virtual origin of the log-law profile
30	κ	von Karman constant
31	ν	kinematic viscosity of water
32	ρ	density of water

1	σ	density of mobile particles
2	τ_p	particle relaxation time
3	τ_*	minimum time-scale of flow fluctuation

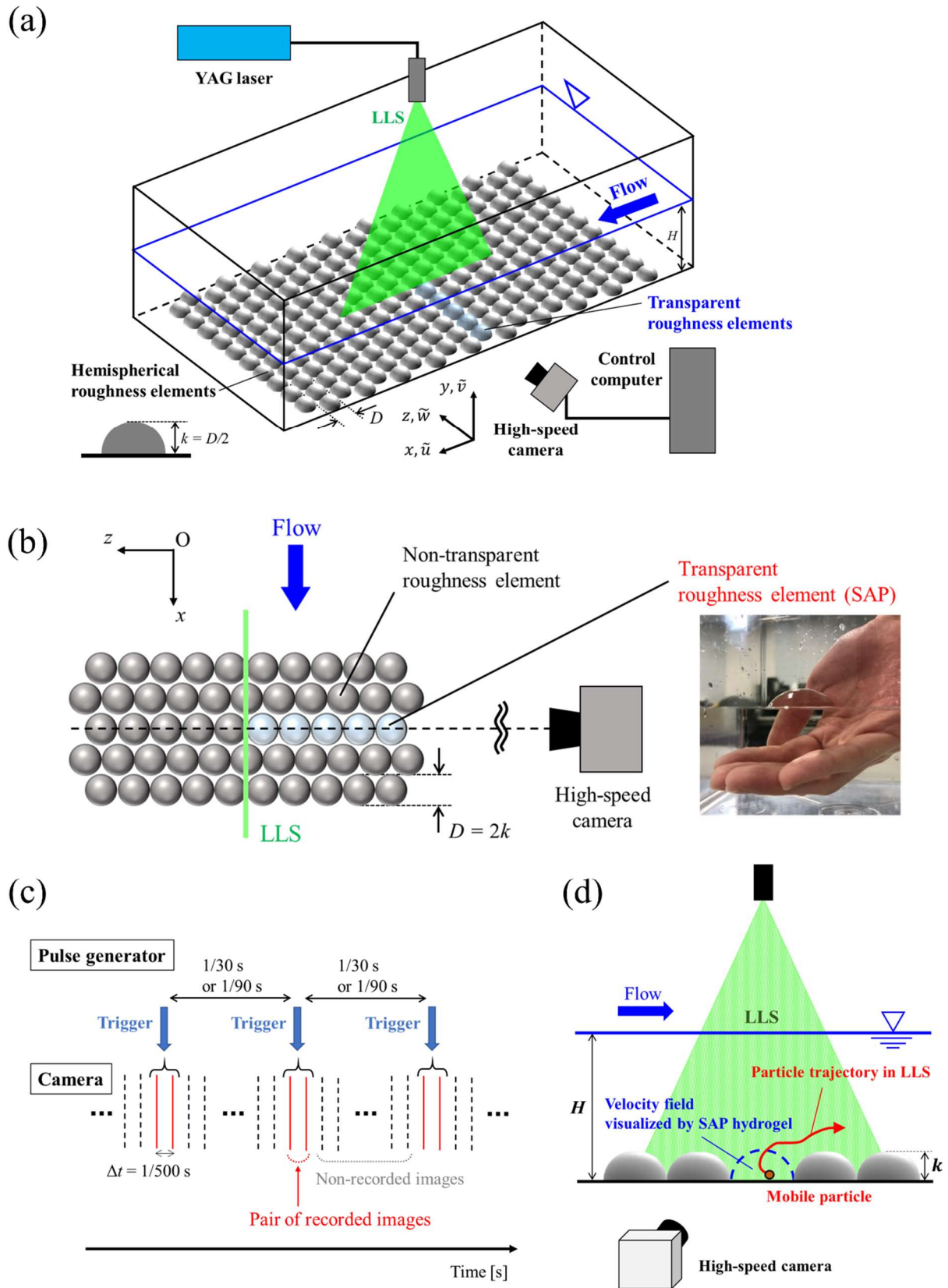
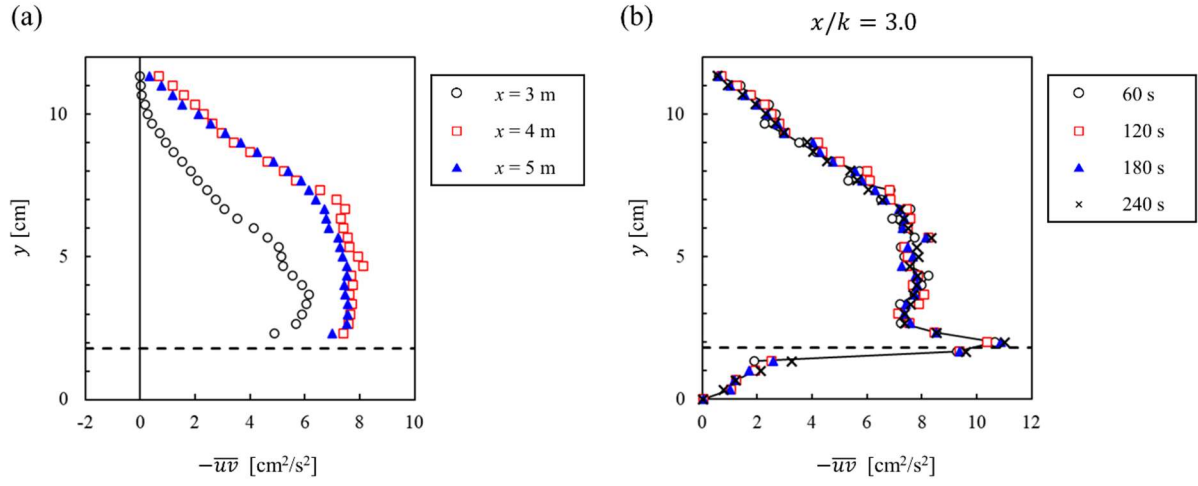


Fig. 1 Experimental set-up: (a) flow velocity measurement by PIV; (b) arrangement of hemispherical roughness elements; (c) conceptual diagram of image data acquisition by the double pulse method; (d) simultaneous measurement of flow and particle velocity



1 **Fig. 2** (a) Streamwise evolution of the vertical distribution of the Reynolds shear stress, $-\overline{u'v'}$ (y), at
2 $x = 3$ m, 4 m (measurement area) and 5 m. (b) Variation of the measured Reynolds shear stress at
3 $x/k = 3.0$ with the measurement duration (60 s, 120 s, 180 s and 240 s)

1 **Table 1** Hydraulic condition

H (cm)	k (cm)	H/k	U_m (cm/s)	u_* (cm/s)	k^+	Re	Fr	Type of experiment
12.0	1.8	6.7	30	3.6	650	36,000	0.28	PIV measurement Particle-tracking experiments: trajectory measurement; PIV for entrainment events

2 **Table 2** Physical properties of mobile particles for the particle-tracking experiment

d (cm)	d_p^+	d/k	σ/ρ	V_t (cm/s)	V_t/u_*	St^+	Sh
0.19	69	0.11	1.21	5.2	1.4	55	0.33

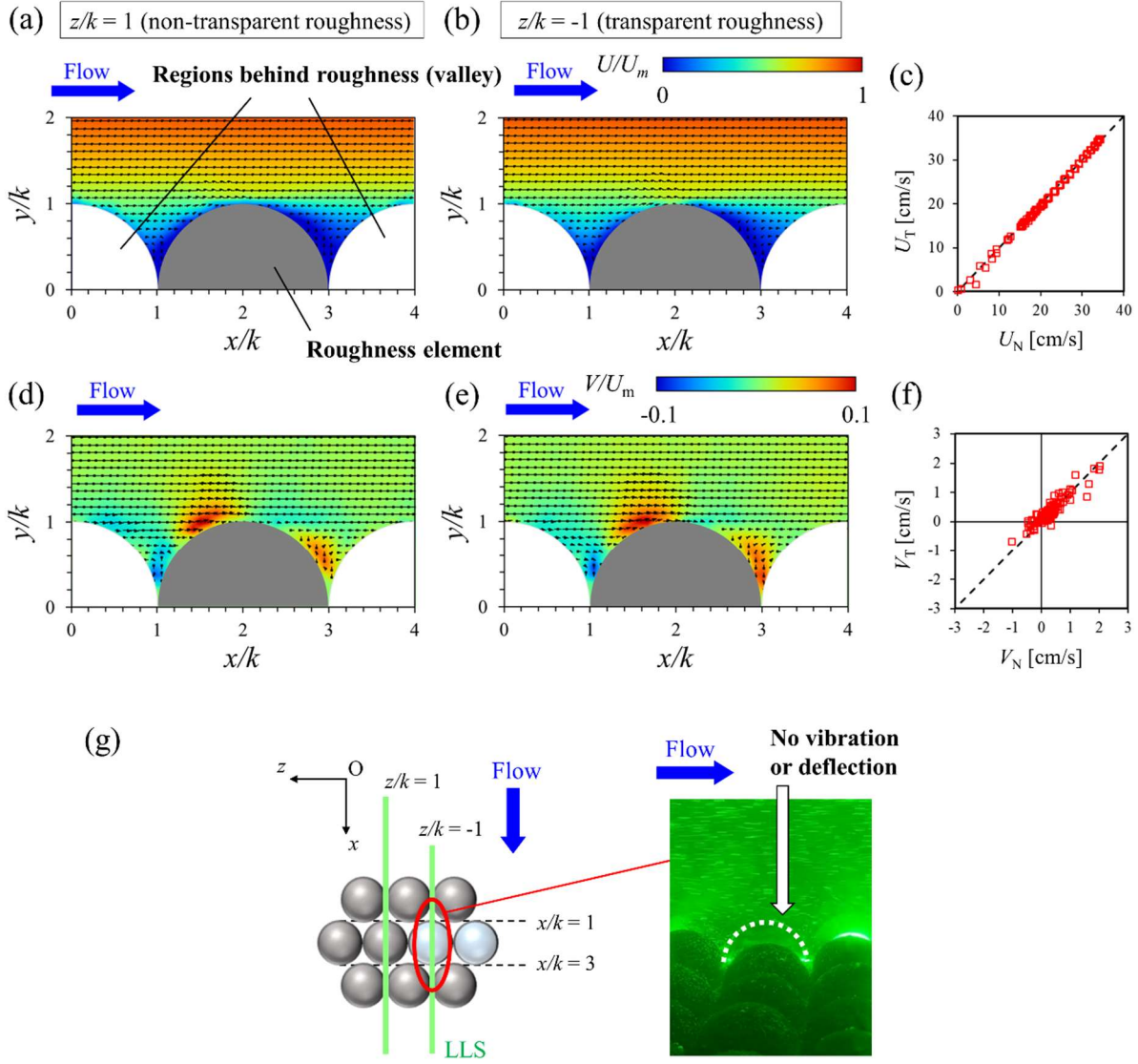
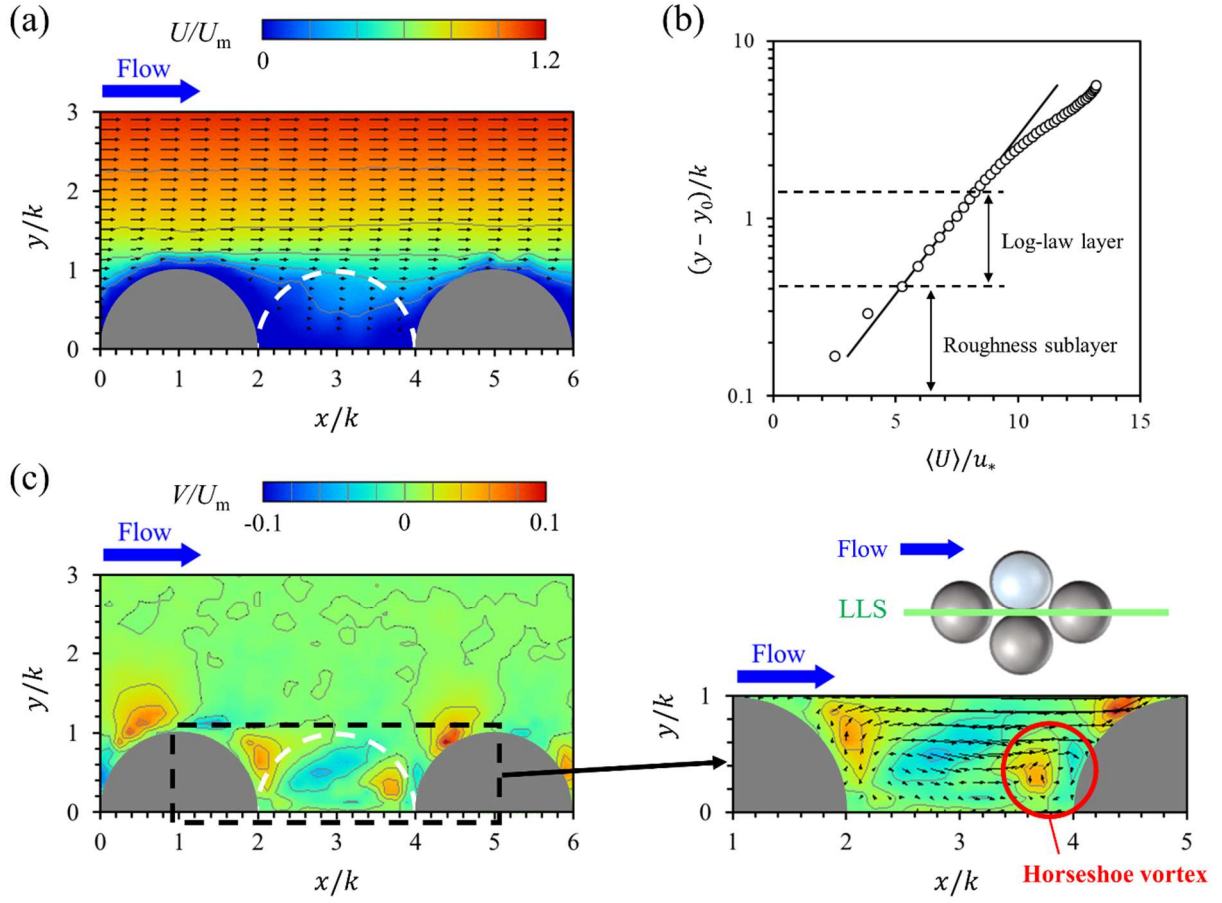
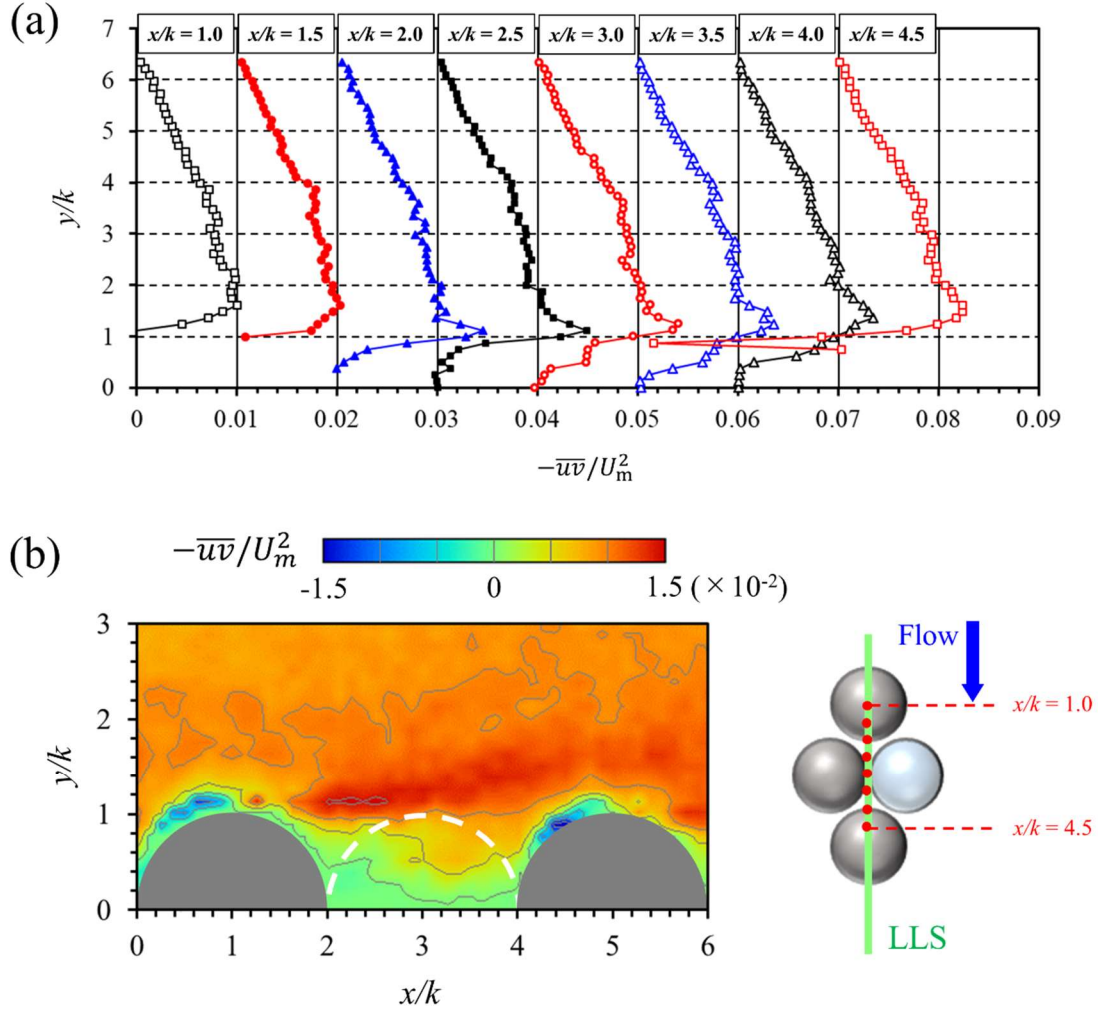


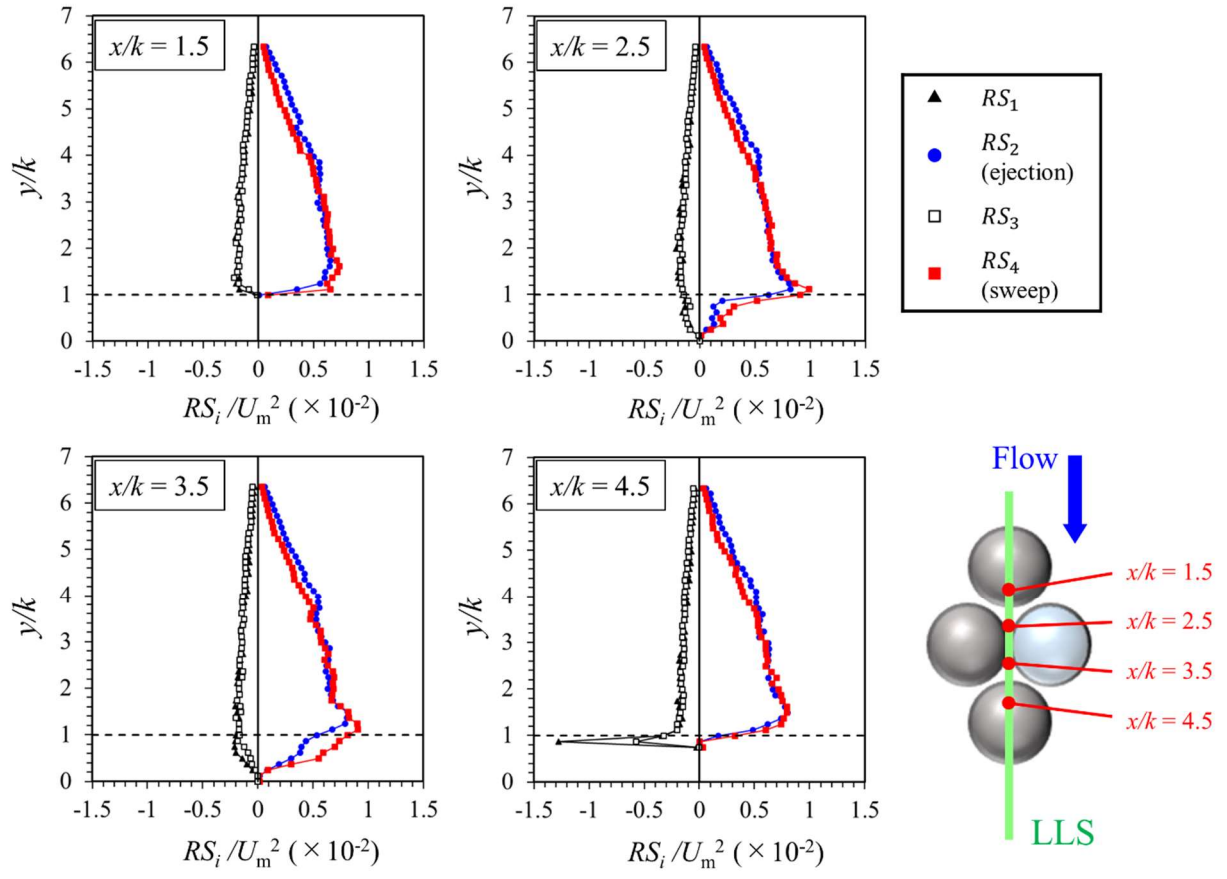
Fig. 3 Contours of (a, b) mean streamwise and (d, e) vertical flow velocity distributions around a non-transparent (a, d) and a transparent roughness element (b, e); (c, f) comparison of the measured time-averaged velocities around a transparent and a non-transparent roughness element; (g) spanwise positions of LLS: $z/k = -1$ and 1



1 **Fig. 4** (a) Contour plot of the time-averaged streamwise flow velocity, U , around roughness
2 elements ($z/k = 0$). (b) Semi-log plot of the spatially and temporally averaged velocity profile,
3 $\langle U \rangle(y)$. (c) Contour plot of the time-averaged vertical flow velocity, V



1 **Fig. 5** Distributions of the Reynolds shear stress, $-\overline{uv}$, over rough wall: (a) vertical profiles at eight
2 points shifted in the streamwise direction (from $x/k = 1.0$ to $x/k = 4.5$); (b) contour map in a
3 vertical plane ($z/k = 0$)



1 **Fig. 6** Vertical profiles of the quadrant Reynolds shear stress at $x/k = 1.5, 2.5, 3.5$ and 4.5

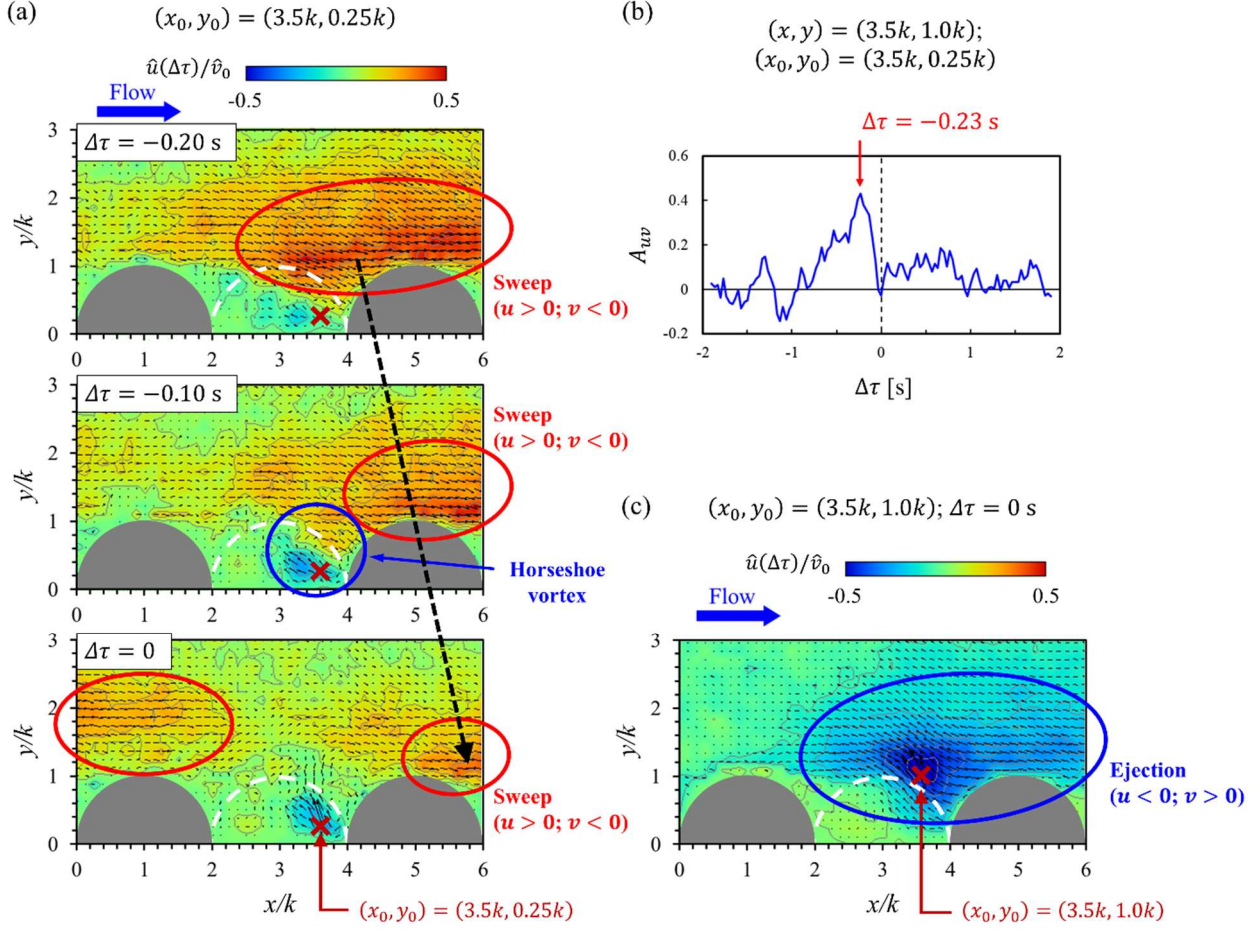


Fig. 7 Conditional velocity field at time $t + \Delta\tau$, $\hat{u}_i(x, y, \Delta\tau)$, given an upward flow event at a fixed reference point (x_0, y_0) at time t ($v(x_0, y_0, t) > 0$). (a) Contour plots of the conditional streamwise velocity, $\hat{u}(x, y, \Delta\tau)$, with a reference point at $(x_0, y_0) = (3.5k, 0.25k)$ ($\Delta\tau = -0.20$ s, -0.10 s and 0). The values are nondimensionalized by $\hat{v}_0 \equiv \hat{v}(x_0, y_0, 0)$. Black vectors denote the vector distribution of $(\hat{u}, \hat{v})$. (b) Variation of the LSE coefficient for the streamwise velocity at $(x, y) = (3.5k, 1.0k)$ with the time lag $\Delta\tau$ ($(x_0, y_0) = (3.5k, 0.25k)$). (c) Contour plot of the conditional streamwise velocity, $\hat{u}(x, y, 0)$, with a reference point at $(x_0, y_0) = (3.5k, 1.0k)$

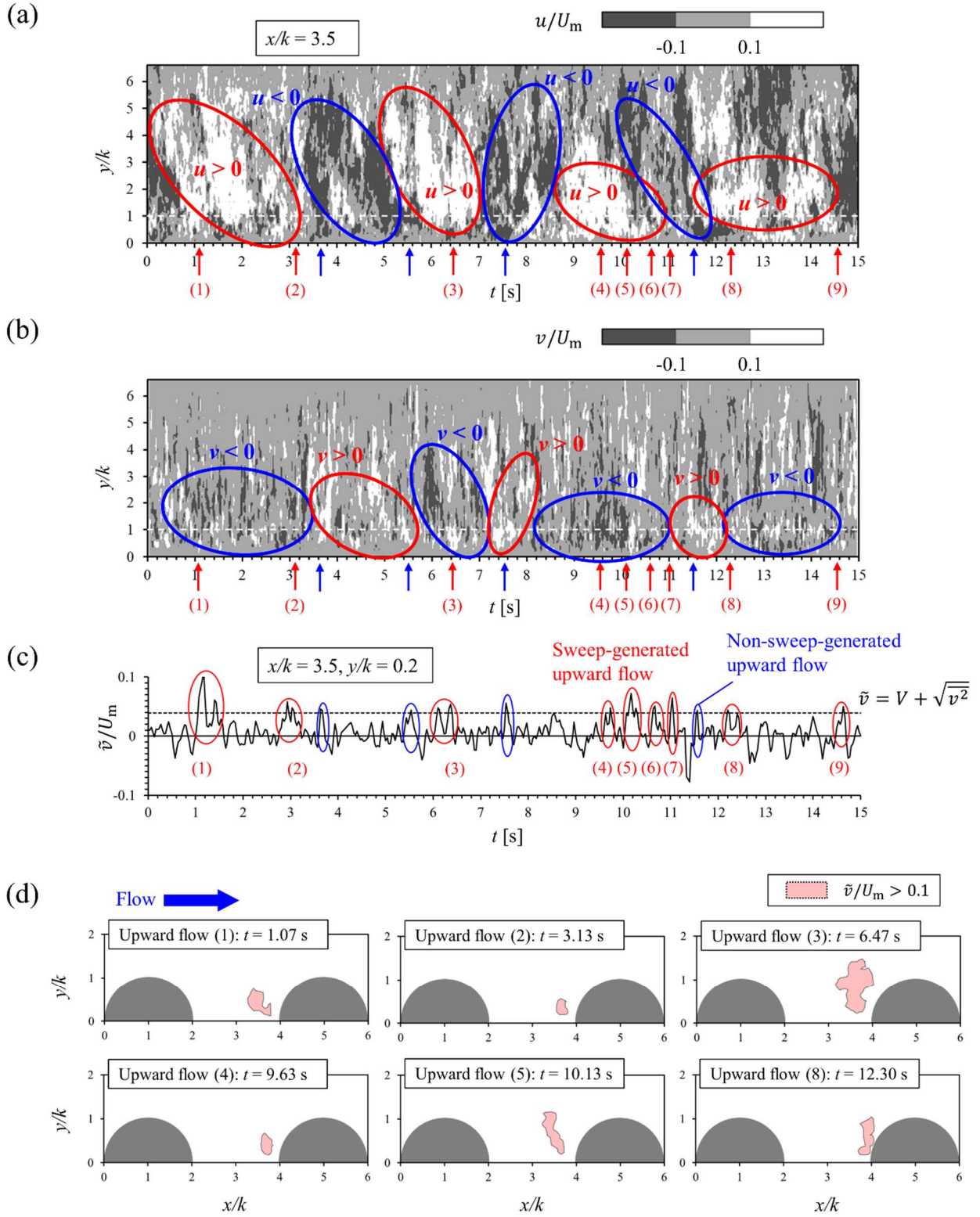


Fig. 8 (a, b) Time-series contour of the streamwise, $u(y)$, and vertical velocity fluctuation profiles, $v(y)$. (c) Time-series of the instantaneous vertical flow velocities, $\tilde{v}(t)$, at $x/k = 3.5$ and $y/k = 0.2$. Arrows in (a, b) and ellipses in (c) indicate strong upward flows ($\tilde{v} > V + \sqrt{v^2}$); especially, red symbols correspond to the sweep-generated ones. (d) Examples of the upward flow region within the valley of the rough bed

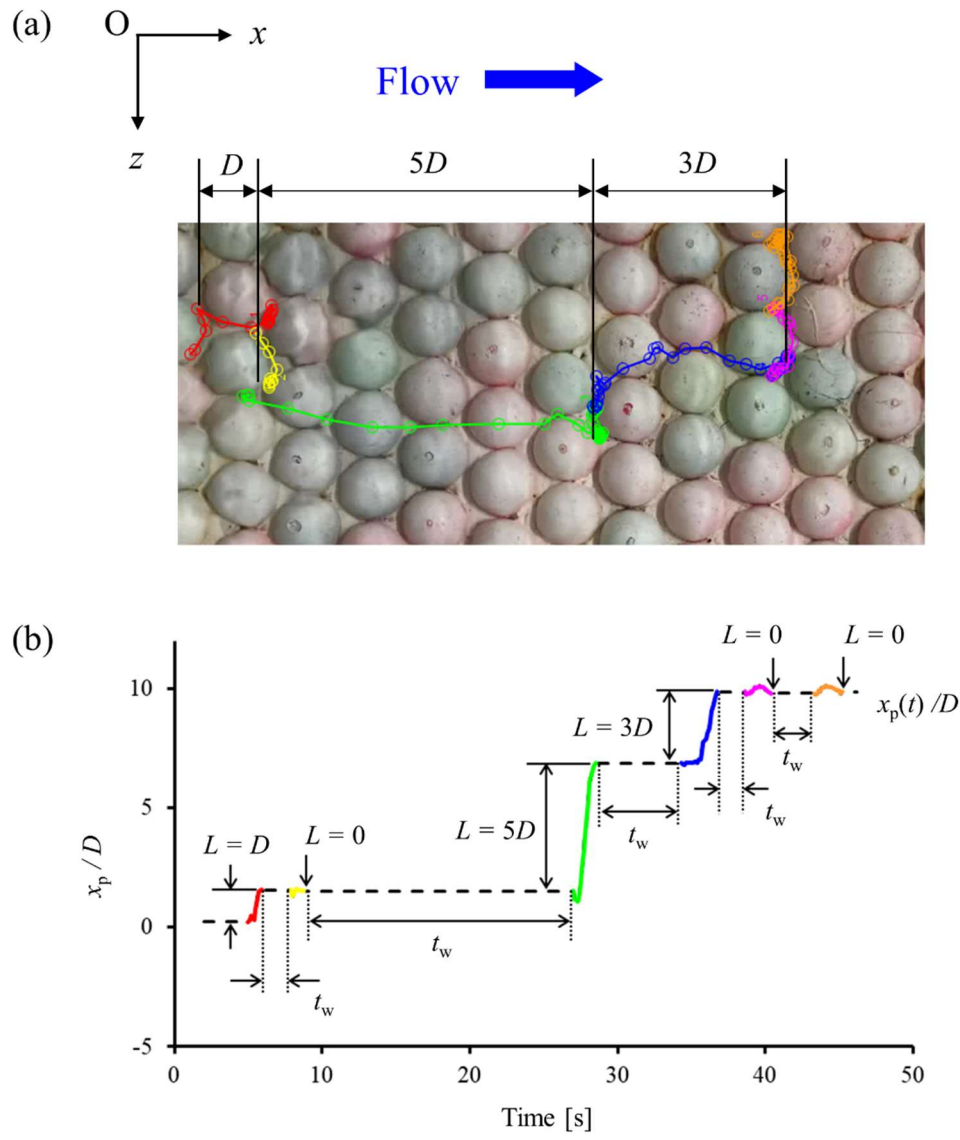


Fig. 9 Example of particle trajectories observed in the particle-tracking experiment: (a) particle motion in the horizontal plane and (b) time-series of the streamwise centroid positions, $x_p(t)$

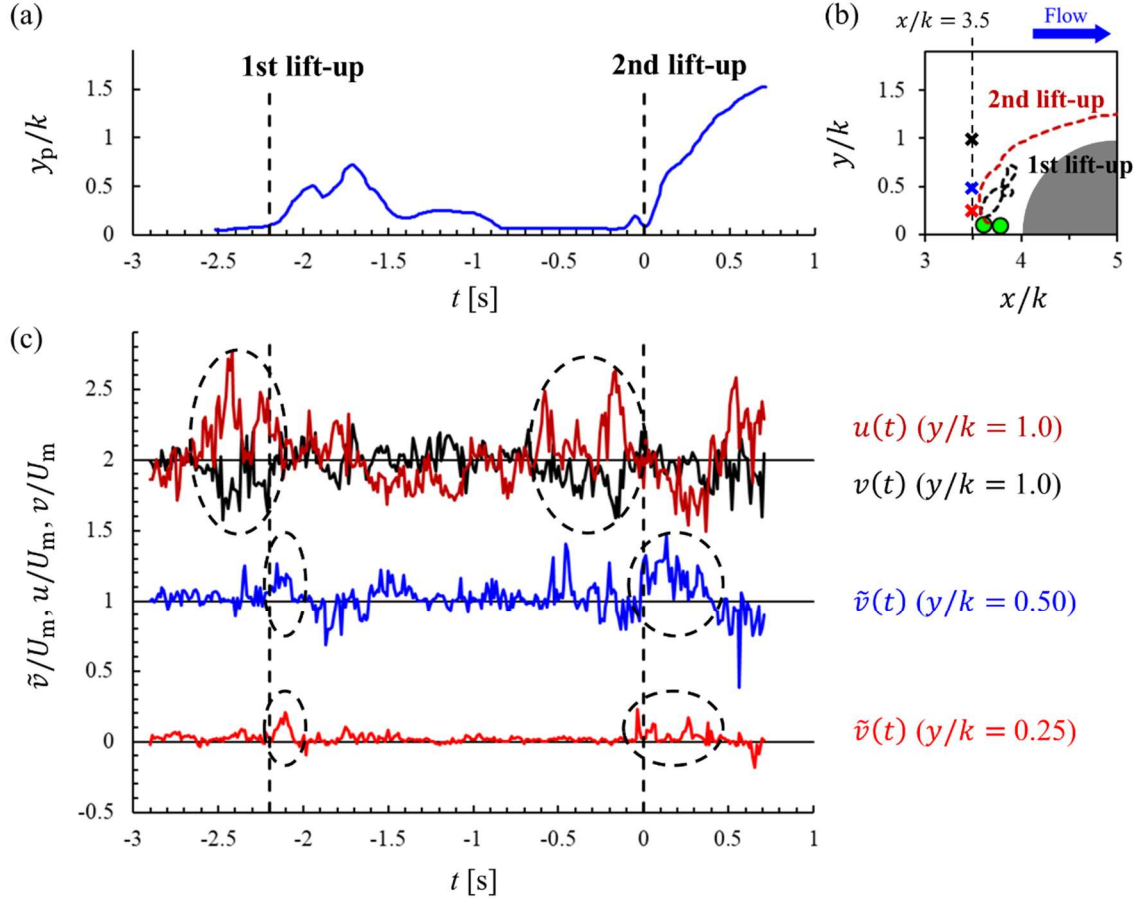


Fig. 10 Two entrainment events between roughness elements: (a) time series of the vertical particle positions, $y_p(t)$; (b) particle trajectory for each event; (c) time series of the instantaneous vertical velocities, $\tilde{v}(t)$, at $y/k = 0.25$ and 0.50 , and the instantaneous velocity fluctuations, $u(t)$ and $v(t)$, at $y/k = 1.0$ ($x/k = 3.5$)

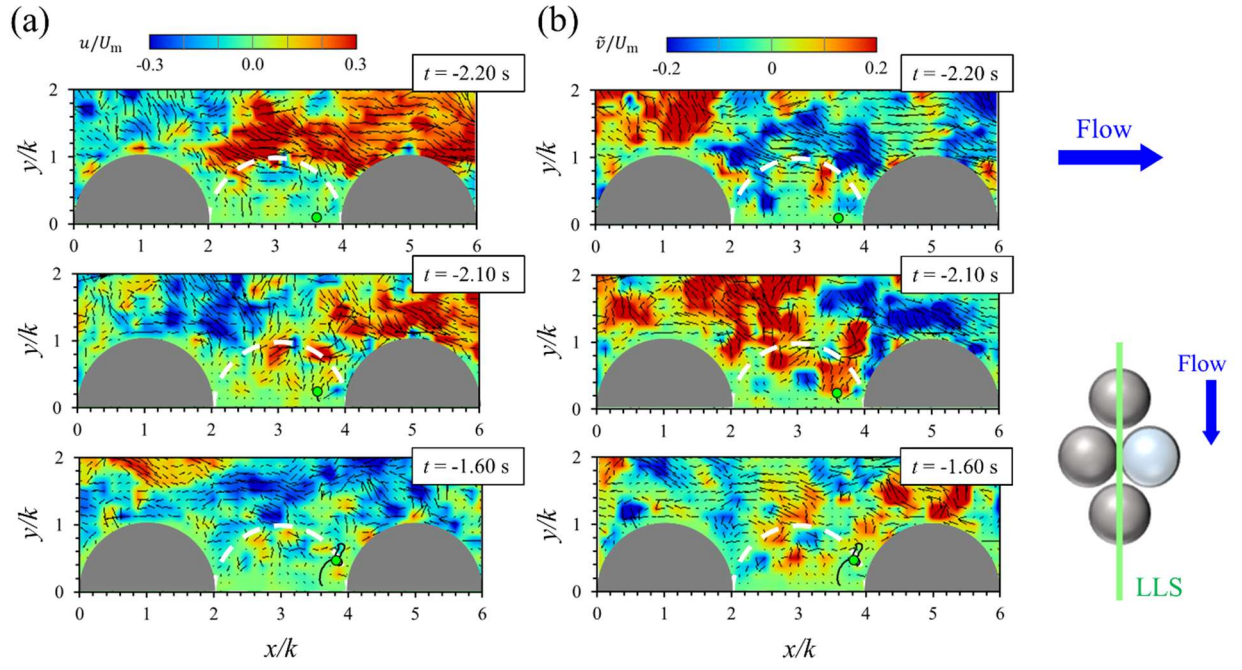
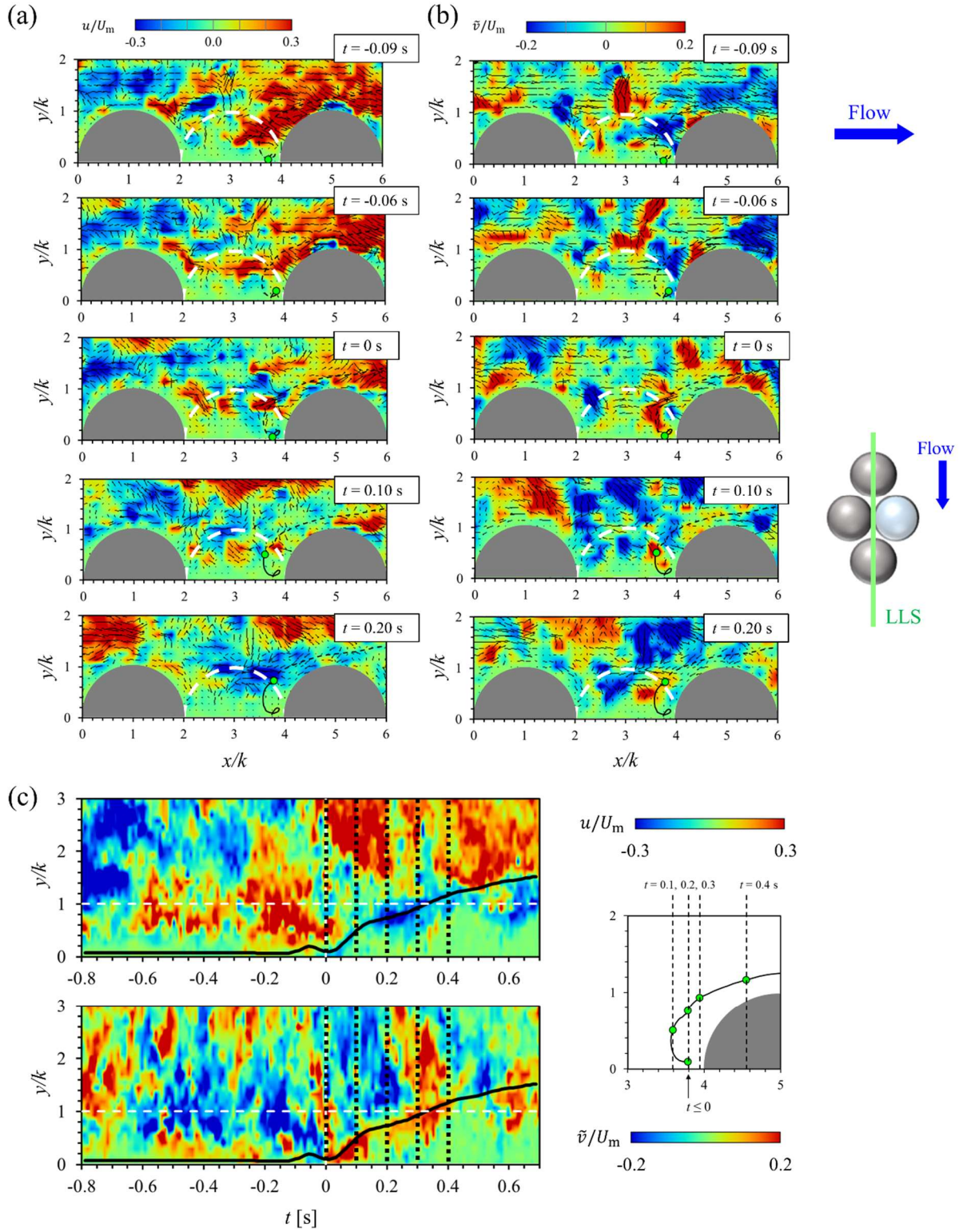


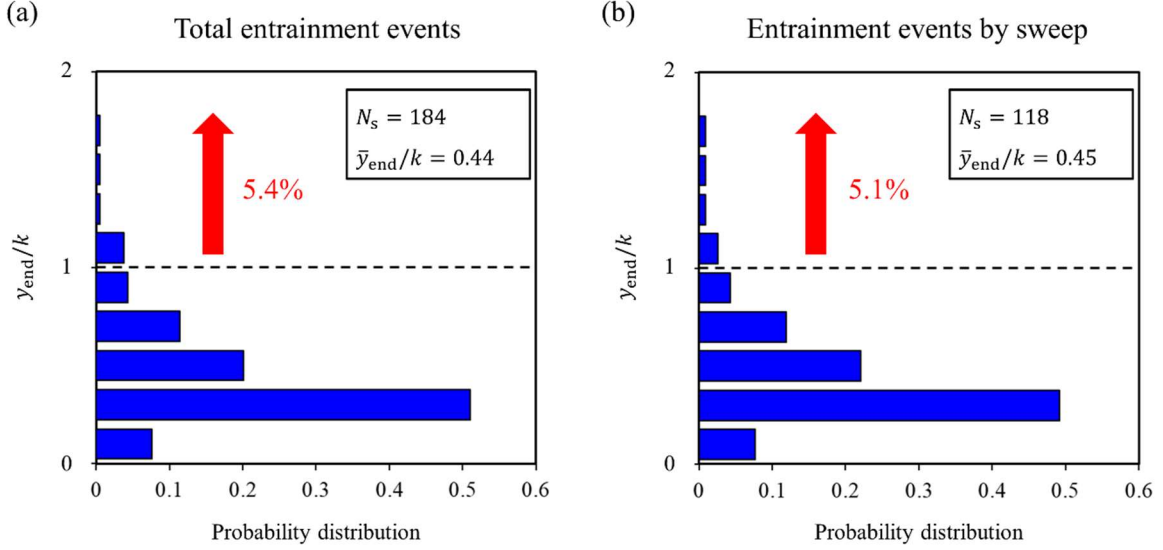
Fig. 11 Sequence of the instantaneous flow fields and the particle centroid positions for '1st lift-up':
 (a) fluctuating streamwise velocities, u ; (b) instantaneous vertical velocities, $\tilde{v}$



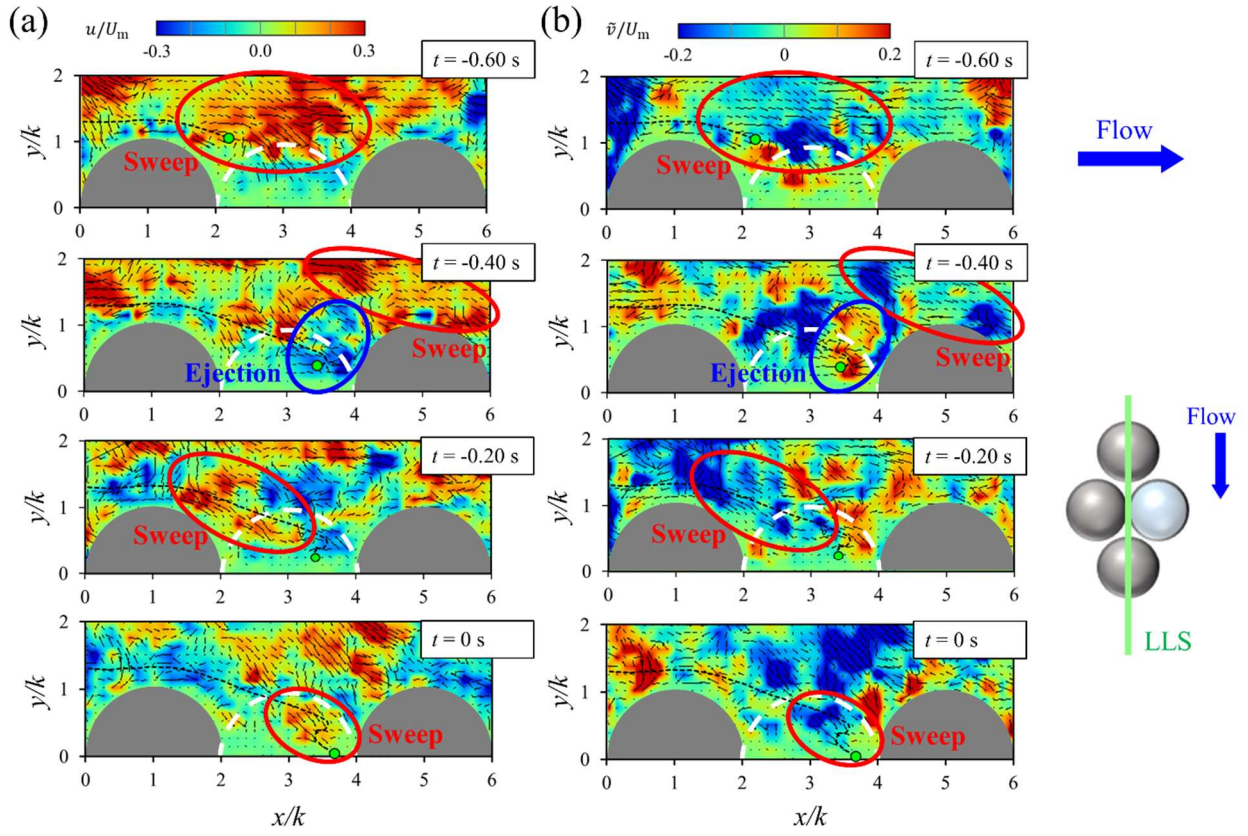
1 **Fig. 12** Sequence of the instantaneous flow fields and the particle centroid positions for ‘2nd lift-
 2 up’: (a) fluctuating streamwise velocities, u ; (b) instantaneous vertical velocities, $\tilde{v}$; (c) Time-series
 3 contours of instantaneous velocity distributions at the streamwise particle positions: $u(x_p(t), y)$
 4 and $\tilde{v}(x_p(t), y)$

1 **Table 3** Classification of the 167 detected entrainment events based on the type of turbulent events
2 that occurred just before the initiation of particle lift-up ($t_{BE} - 0.3 [s] \leq t \leq t_{BE} - 0.1 [s]$). The
3 reference points for the flow velocity data are two points around the roughness height ($x = 3.5k$;
4 $y = 1.0k$ and $1.5k$)

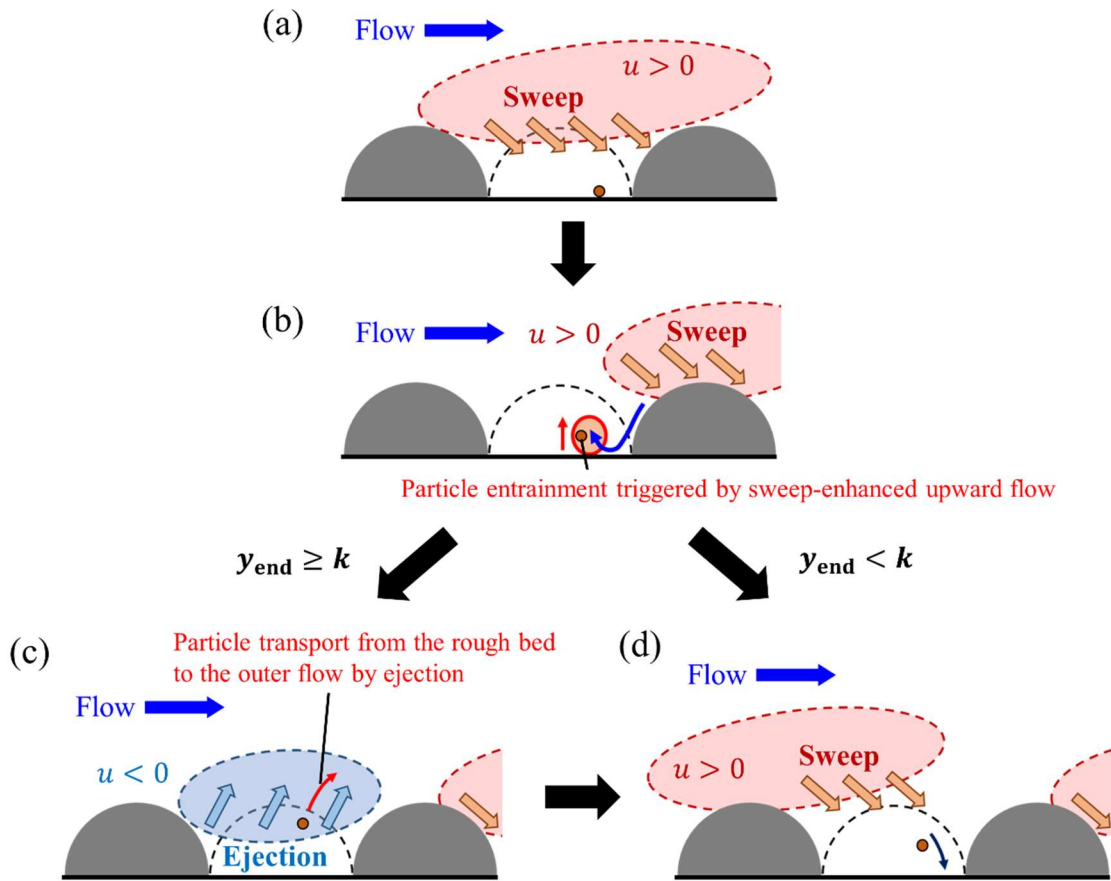
	Number of events (% of the total events)	
	at $x = 3.5k$; $y = 1.0k$	at $x = 3.5k$; $y = 1.5k$
Entrainment by sweep (Q4) or ejection (Q2):		
$\bar{u}_{BE} > U$ with sweep ($u > 0$; $v < 0$; $-uv > \bar{u}\bar{v} $)	118 (70.7%)	121 (72.5%)
$\bar{u}_{BE} < U$ with ejection ($u < 0$; $v > 0$; $-uv > \bar{u}\bar{v} $)	39 (23.4%)	42 (25.1%)
Otherwise	10 (6.0%)	4 (2.4%)



5 **Fig. 13** Probability distributions of the vertical position at termination of an upward motion from
6 the bottom, y_{end} : (a) total entrainment events; (b) entrainment events triggered by sweep



1 **Fig. 14** Sequence of the instantaneous flow fields and particle centroid positions for the particle
2 entrapment: (a) fluctuating streamwise velocities, u ; (b) instantaneous vertical velocities, $\tilde{v}$



1 **Fig. 15** Conceptual model of the particle transport mechanism over rough bed