

Three-dimensional time-averaged turbulent flow structures and suspended sediment motion in a narrow open channel with rough-bed

Y. Fukushima

Chuo University, Tokyo, Japan

Y. Takakuwa

Research and Development Initiative Chuo University, Tokyo, Japan

S. Fukuoka

Research and Development Initiative Chuo University, Tokyo, Japan

ABSTRACT: Three-dimensional numerical experiments were conducted in a narrow open channel rough surface turbulent flow field to investigate the three-dimensional structure of the flow and the motion of suspended sediment. The time-averaged flow structure obtained from this analysis indicates that the outer secondary flow (OSF), which moves up along the sidewall from the bottom corner, and the bottom secondary flow (BSF), which moves from the bottom corner toward the center of the channel, occur in the narrow open channel. It was found that the suspended particles reduced the vertical flow velocity near the sidewall and that particles were captured in the instantaneous upwelling flow mass and particle motions are greatly affected by the surrounding instantaneous flow velocity.

1 INTRODUCTION

Sediment transport during floods has a significant impact on channel morphology and the river environment. Therefore, it is an important engineering issue to properly evaluate the flow structure and sediment transport according to the channel boundary geometry.

As shown in Figure 1, urban rivers such as the Kanda River, which flows through central Tokyo, are narrower and have smaller aspect ratios (B/h) during flood peaks (Numata (2013)). In the vicinity of the sidewall of the channel, as shown in Figure 2, there are three types of secondary flows: the Outer Secondary Flow (OSF), which flows up along the sidewall from the bottom corner, the Bottom Secondary Flow (BSF), which flows from the bottom corner to the center of the channel, and the Inner Secondary Flow (OSF), which rotates in the opposite direction at the corner between the water surface and the sidewall (Grega et al. (1995), Nezu and Nakagawa (1993)). Furthermore, Thorne (1978) suggested that secondary flow of second kind occurs in the

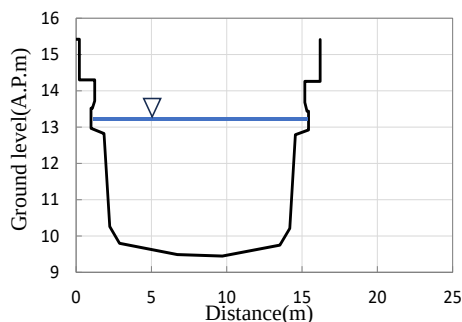


Figure 1. Cross-sectional of the Kanda River (Tajima Bridge) and maximum water level of the December 2010 flood.

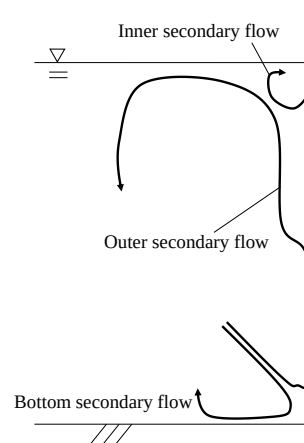


Figure 2. Secondary flow of Plantl's second kind.

river from the mainstream velocity distribution and the distribution of secondary flow. That secondary flows of second kind may have a significant impact on sediment transport patterns, including scouring near riverbanks, and on riverbank erosion.

However, the effects of sidewalls and roughness factors on the three-dimensional structure of the flow and the relationships among secondary flow, turbulence, and suspended sand movement in a rough open channel turbulent field dominated by secondary flow of Prandtl's second kind are not fully understood.

In this study, the Arbitrary Particle Multiphase (APM) method (Fukuoka et al. (2014)), which is capable of solving flow fields with highly concentrated gravels, was used to analyze the three-dimensional time-averaged structure of the flow with a narrow width and a cylinder roughness laid on the bottom. Next, the effects on the motion of suspended particles of ambient velocity, and are investigated.

2 EXPERIMENTAL CONDITIONS

Figure 3 shows a schematic diagram of the channel. The numerical experimental channel used in this study was assumed to be an urban river such as the Kanda River. It is not realistic to analyze a channel equivalent to the scale of a real river because the computational load for a three-dimensional numerical experiment is very large. We considered that the basic three-dimensional structure of the flow and the mechanical motion mechanism of suspended particles would not change much if the aspect ratio (b/h) of the channel is similar, even if the channel scale is different.

In this study, steady flow was supplied to a uniform straight channel 1.5 m long, 0.02 m wide, and with a slope of 1/20. The bottom surface was covered with cylindrical roughness with a radius of 4 mm. The coordinate axes are x-axis in the flow direction, y-axis in the cross-sectional direction, and z-axis in the vertical upward direction. 2 cases were analyzed: Case 1 is a clear flow with no particles; Case 2 is a spherical particle with a diameter of $d = 1$ mm. Since the scale of the channel is small, the intensities of secondary flow and turbulence are also small, the time-averaged vertical upward flow velocity was compared with the settling velocity of the particles, and the particle specific gravity was set to 1.2 so that the particles would be in suspended motion. The initial velocity of the particles was given as the velocity at the closest velocity evaluation point from the particle center coordinates to follow the flow; referring to the method of Rodi et al. (2013), the flow velocity at a distance of 20 roughness elements from the upstream end ($x=0.16$ m) was given for the velocity at the upstream end of the channel ($x=0.00$ m) from time to time. This was considered to shorten the distance over which the boundary layer develops and to make the motion of suspended particles independent of the channel length. At the downstream end ($x=1.50$ m), the velocity at one upstream evaluation point was given so as to control the depth at the downstream end. The turbulence data were measured for 6 s every 4.0×10^{-4} s after the flow field had fully developed, following the method of Nezu (1977). Table 1 shows the hydraulic quantities for the experiments.

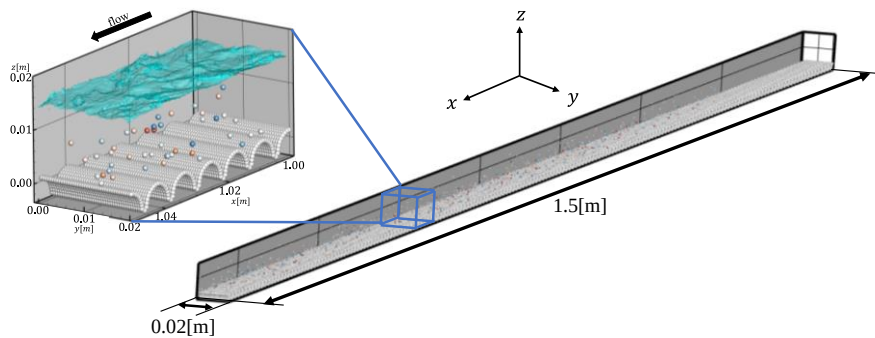


Figure 3. Numerical movable-bed channel and the coordinate system

Table1. Experimental conditions

	Case1	Case2	
Discharge	0.170	0.170	l/s
Hydraulic radius	5.87	5.87	mm
Water depth	14.2	14.2	mm
Aspect ratio	1.41	1.41	-
Radius of roughness element	4.00	4.00	mm
Relative depth	3.55	3.55	-
Mean velocity	59.9	59.9	cm/s
Bed shear velocity	5.36	5.36	cm/s
Reynolds number	3510	3510	-
Particle Reynold number	-	5	-
Froude number	2.50	2.50	-

3 NUMERICAL METHOD

This analysis uses the APM method by Fukuoka et al. (2014) to solve the flow by Eulerian and the particles by Lagrangian approach.

For the flow analysis, turbulence larger than the computational grid is solved directly, while smaller turbulence is modeled using LES, which is capable of capturing the instantaneous structure of the flow. The governing equations are shown below.

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{Du_i}{Dt} = g_i - \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \{2(\nu + \nu_{SGS})S_{ij}\} \quad (2)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3)$$

$$\nu_{SGS} = (C_s \Delta)^2 \sqrt{2S_{ij}S_{ij}} \quad (4)$$

where u_i = i-directional component of mass-averaged velocity; P = sum of isotropic components of SGS stress; g_i = i-directional component of gravitational acceleration; ρ = volume-averaged density; ν = kinematic viscosity; ν_{SGS} = SGS turbulent viscosity; S_{ij} = strain rate tensor; C_s = Smagorinsky constant (=0.173); Δ = computational grid width. A single fluid model is applied to the boundary between the particles and the fluid in the computational grid to account for the effect of particle motion on the flow. The free surface is evaluated using the volume-of-fluid method. The equations of motion for translation and rotation are solved for individual particles simultaneously with the flow analysis.

$$M\ddot{r}_i = Mg_i + F_i^f + F_i^c \quad (5)$$

$$\dot{\omega}_i = I_{ij}^{-1} \{ R_{ji} (T_i^f + T_i^c) - \varepsilon_{jkl} \omega_k I_{lm} \omega_m \} \quad (6)$$

where index i = the components of the global coordinate system fixed on the space; the indices i, m = the components of the local coordinate system fixed on a rigid body; M = mass of a particle; g_i = gravitational acceleration; r_i = position of the center of gravity of the rigid; F_i = force acting on the surface of the particle; suffix f, c = components of the fluid forces and contact forces between particles, respectively; ω_i = angular velocity; T_i = torque on the center of the gravity generated by the force; I_{ij}^{-1} = inverse of the matrix consisting of the components of the moment of inertia tensor in the local coordinate system; R_{ji} = equal to $e_j \cdot e_i$ (e_j and e_i are unit basis vectors); ε_{ijk} = Levi-Civita symbol. The contact forces between particles, between particles and the channel bed, and between particles and sidewalls are calculated using the discrete element method (Cundall and Strack (1979), Johnson (1985)). For this reason, the sidewalls and roughness elements consist of particles of 1 mm diameter. The fluid forces acting on the particles are calculated by volume integration of the pressure and shear stress gradient terms of the equation of motion obtained from the detailed flow field around the particles, using a computational grid width smaller than the particles. Table 2 shows the analytical parameters.

Table 2. Simulations parameters.

$\Delta x, \Delta y, \Delta z$: the size of the fluid computation cell	0.00025	m
d/Δ : Ratio of grain size to fluid calculation grid width	4	-
$\Delta/\Delta_{subcell}$: Ratio of computed lattice width to subcell width	6	-
Δt^f : Time step for the fluid simulation	2.0×10^{-5}	s
Δt^p : Time step for the particle simulation	2.0×10^{-7}	s
Density of water	1000	kg/m ³
Density of particles	1200	kg/m ³
Smagorinsky constant	0.173	-
Elastic modulus	2.0×10^4	kg/cm ²
Poisson's ratio	0.388	-
Coefficient of repulsion	0.5	-
Coefficient of friction	0.38	-

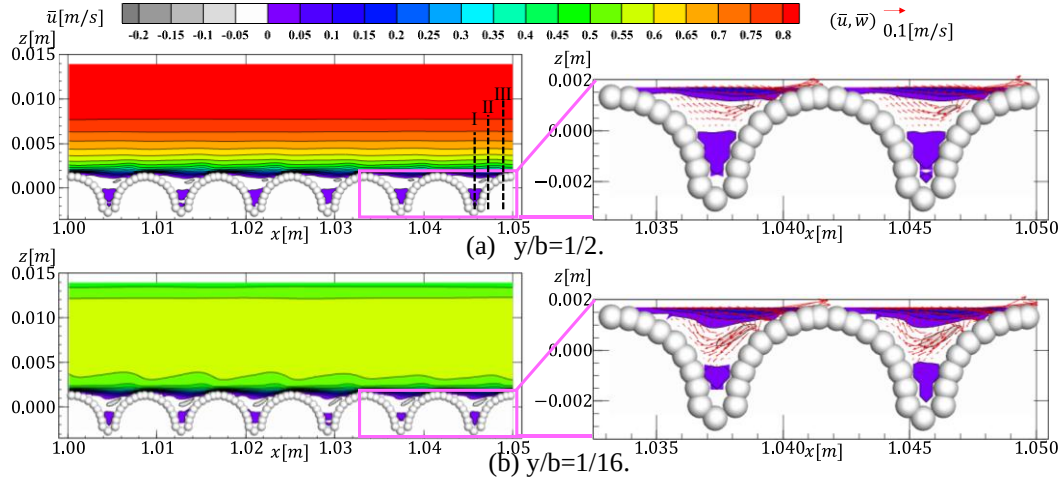
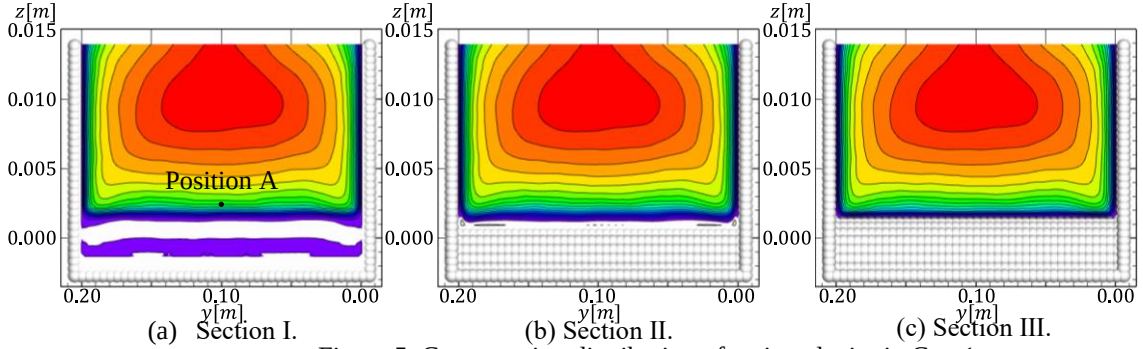
Figure 4. Longitudinal distribution of mainstream velocity at $y/b=1/2$ and $y/b=1/16$ in Case1.

Figure 5. Cross-section distribution of main velocity in Case1.

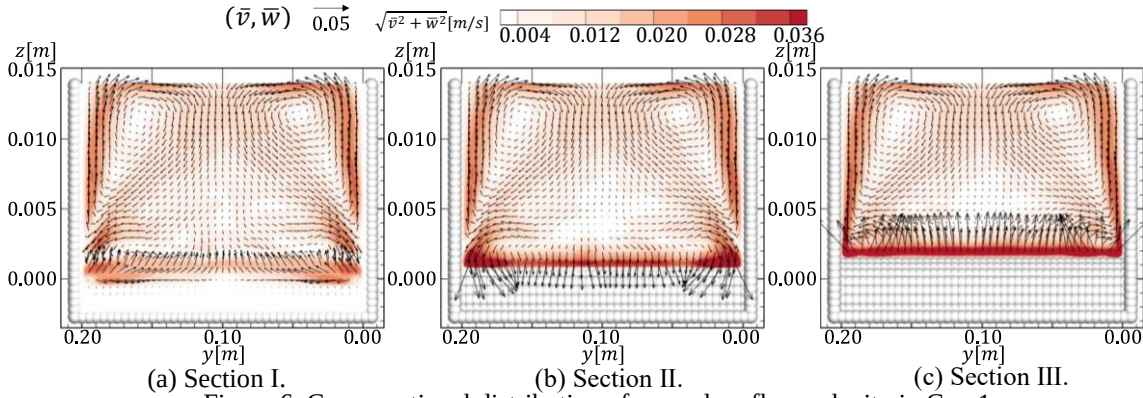


Figure 6. Cross-sectional distribution of secondary flow velocity in Case1.

4 RESULTS AND DISCUSSIONS

4.1 Time-averaged flow structure

Figure 4 shows the longitudinal distribution of the main flow velocity along the channel centerline ($y/b=1/2$) and very close to the sidewall ($y/b=1/16$) in Case 1. In the region between the roughness elements, the flow overcoming one upstream roughness element impinges on the front surface of the following roughness element, forming a vortex. Although roughness elements distort the main flow velocity distribution in the vicinity of roughness elements, its effect on the fluid at higher locations is small, and the longitudinal change in the main flow velocity distribution is small.

Figure 5 shows the cross-sectional distribution of the main flow velocity in Case 1. The location of the cross-section is shown in Figure 4(a). As mentioned above, the longitudinal distribution of the main flow velocity changes little. The velocity dip phenomenon, in which the maximum main-stream velocity occurs below the water surface, is observed.

Figure 6 shows the cross-sectional distribution of secondary flow velocity in Case 1. The longitudinal variation for one half of the roughness element is considered. The BSF and OSF are clearly visible in Section I. The flow that overcomes one of the upstream roughness elements impinges on the roughness front, and is divided into a flow that dives toward the roughness valley and a flow that overcomes the roughness element. In Section II close to the roughness valley, the downward component of the BSF overlaps with the flow that dives into the roughness valley, and strong downward flow velocity is generated at the bottom corner. On the other hand, in Section III a cross section near the top of the roughness, the flow over the roughness elements overlaps with the upward component of the OSF, resulting in strong upward flow at the bottom corner.

As mentioned above, due to the overlap of OSF and BSF with vertical velocity, the ratio of maximum secondary flow velocity $|\bar{s}\bar{v}_{max}|$ to the maximum main flow velocity $\bar{u}_{max}$ is larger in a rough-surface open channel than in a smooth-surface open channel ($|\bar{s}\bar{v}_{max}|/\bar{u}_{max} = 0.015 \sim 0.03$ (Nezu and Nakagawa(1993))); $|\bar{s}\bar{v}_{max}|/\bar{u}_{max}$ in Case 1 is 0.129. Furthermore,

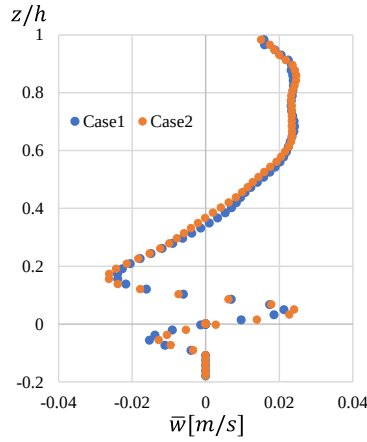


Figure 7. Vertical distribution of vertical velocity($y/b=1/16$).

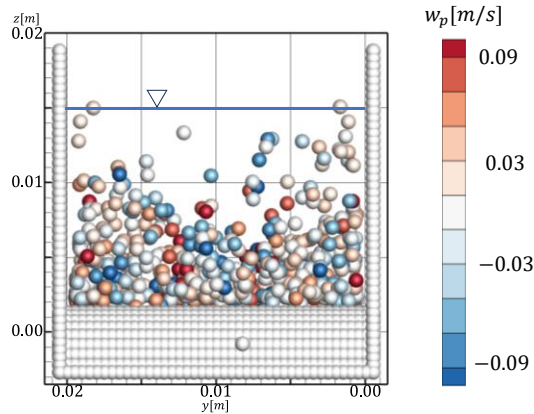


Figure 8. Particle suspension viewed from upstream to downstream of the channel in Case2.

since the OSF carries slow momentum near the sidewall to the water surface in the center of the channel, the main flow velocity distribution is distorted and velocity dip phenomenon occurs, as shown in Figure 5. This increase in secondary flow intensity in a rough-surface open channel is thought to occur even in a real river with a rough bed.

It is also confirmed that the mainstream and secondary flow structures of Case 2, including particles, are almost the same as those of clear flow in Case 1.

Figure 7 shows the time-averaged vertical distribution of vertical velocity near the sidewall ($y/b=1/16$). Case 2, which contains particles, has a smaller vertical velocity near $z/h=0.3$ than Case 1. Thus, it was confirmed that particles have an effect on the secondary flow in the cross-section, such as the vertical velocity, but have very small effect on the main flow velocity.

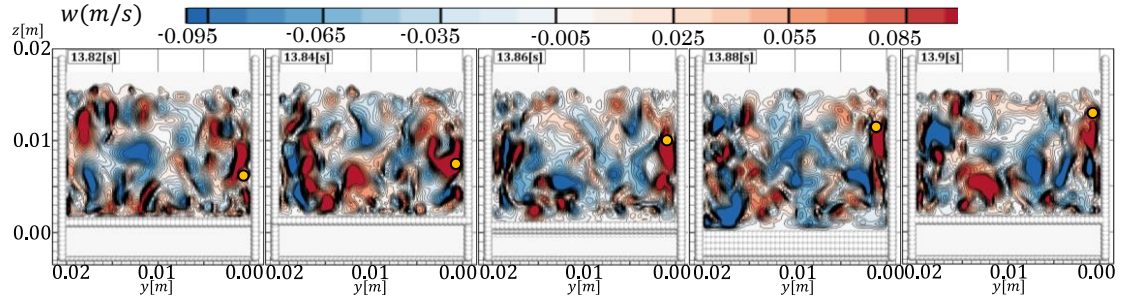


Figure 9(a). Particles rising along the side wall (Particle A) and ambient vertical velocity.

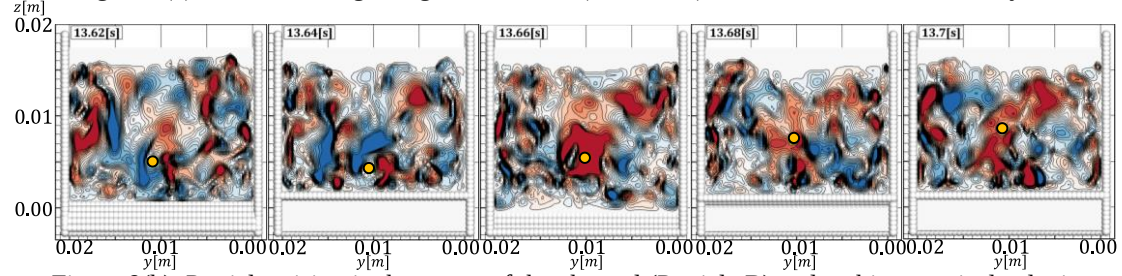


Figure 9(b). Particles rising in the center of the channel (Particle B) and ambient vertical velocity.

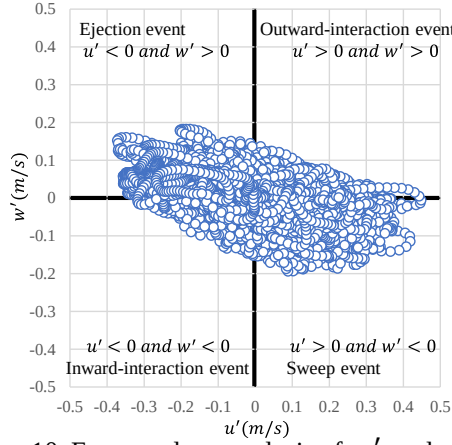


Figure 10. Four quadrant analysis of u' and w' .

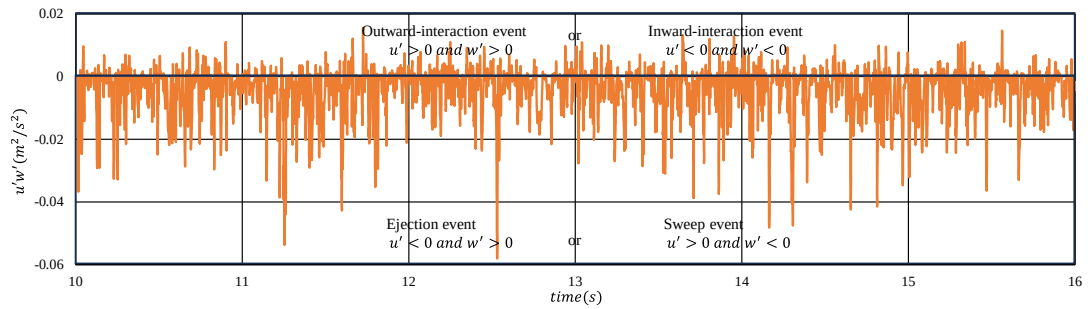


Figure 11. Time series data of instantaneous Reynolds stress.

4.2 Suspended sediment motion and instantaneous flow velocity

Figure 8 shows a view of the channel from upstream to downstream at a given moment in Case 2. Only particles present at $0.6\text{m} \leq x \leq 1.5\text{m}$ are shown, and the volume fraction of particles is 0.11%. The color of a particle indicates its vertical velocity (w_p). As shown in the time-averaged cross-sectional distribution of secondary flow velocity in the previous section, the upward velocity occurs only near the sidewalls. However, particles also rise to 60-70% of the water depth near the center of the channel. As a result, suspended particles are greatly affected by the instantaneous flow velocity. In this chapter, the relationship between the instantaneous flow velocity around particles, ejection and sweep near the bottom, and particle motion is discussed.

Figure 9 shows the instantaneous velocities of the particle of interest and its surroundings. The contour is the cross-sectional distribution of the vertical velocity at the longitudinal position of the particle of interest. Particle A is a particle ascending along the sidewall, and Particle B is a particle ascending near the center of the channel. Along the sidewall, there is a fluid mass with strong vertical upward velocity intermittently, as shown in Figure 9(a). Near the center of the channel, the fluid mass with strong vertical upward flow velocity does not reach the vicinity of the water surface. As a result, particle B rises to only about 70% of the water depth, as shown in Figure 9(b).

Next, we examine the relationship between particle motion and ejection and sweep of turbulence. In general, the bursting including ejection and sweep is defined by dividing the flow into four quadrants, taking the variation components $u' (= u - \bar{u})$ and $w' (= w - \bar{w})$ of the main flow velocity and vertical velocity, respectively. The first quadrant is the outward-interaction, the third quadrant is the inward-interaction, the second quadrant is the ejection, and the fourth quadrant is the sweep.

Figure 10 and Figure 11 show the four-quadrant classification of u' and w' at point A (in Figure 5) in the center of the channel and near the bottom of Case 2, and the time series data of instantaneous Reynolds stress $-u'w'$. In the time series data, the instantaneous Reynolds stress greater than 0 indicates an outward-interaction or an inward-interaction, while the instantaneous Reynolds stress less than 0 indicates an ejection or a sweep. The outward-interaction in the first quadrant and the inward-interaction in the third quadrant are smaller than the ejection in the second quadrant and the sweep in the fourth quadrant. For this reason, we considered the outward-interaction and inward-interaction to be negligible in this study.

Therefore, in the present study, ejection and sweep are distinguished by dividing the instantaneous Reynolds stress $-u'w'$ into the following cases, referring to Noguchi (2010).

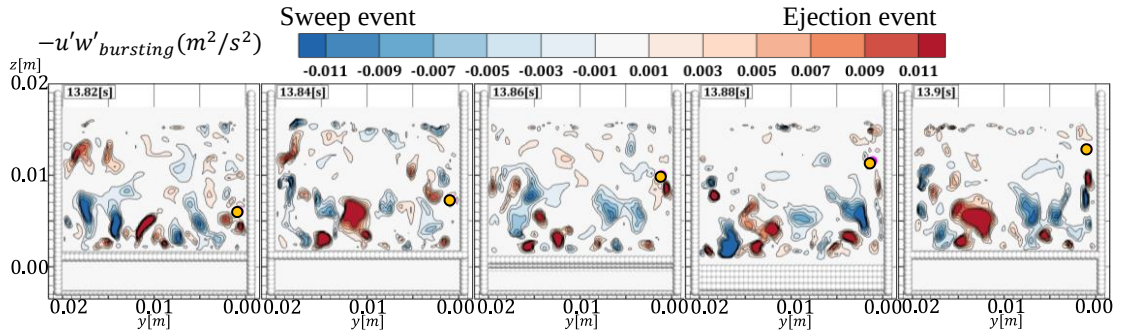


Figure 12(a). Particles rising along the side wall (Particle A) and Location of sweep and ejection.

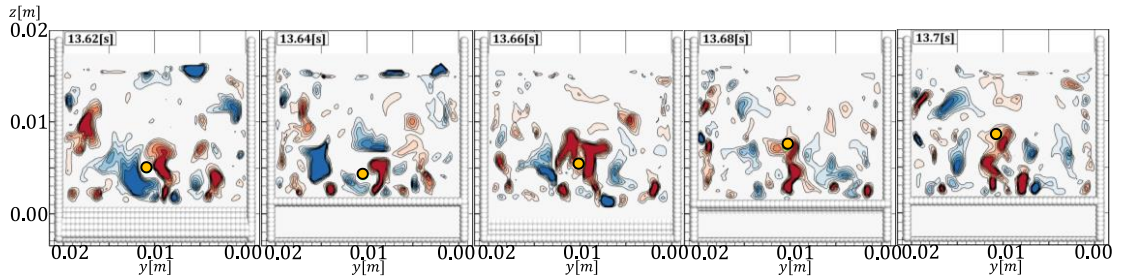


Figure 12(b). Particles rising in the center of the channel (Particle B) and location of sweep and ejection.

$$-u'w'_{bursting} = \begin{cases} 0 & \text{for } u' > 0 \text{ and } w' > 0 \\ -u'w' & \text{for } u' < 0 \text{ and } w' > 0 \\ 0 & \text{for } u' < 0 \text{ and } w' < 0 \\ u'w' & \text{for } u' > 0 \text{ and } w' < 0 \end{cases} \quad (7)$$

Figure 12 shows the positions of the ejection and sweep around particle A, particle B, and of their surroundings. The red area indicates the region where ejection occurs, and the blue area indicates the region where sweep occurs. Ejection occurs around particle B rising near the center of the channel, while neither ejection nor sweep exists around particle A rising near the sidewall. This suggests that particles near the center of the channel are swept up by ejection, while particles near the sidewalls are carried by the time-averaged vertical flow, and that the particles near the sidewalls and those near the center of the channel have different mechanisms of suspension.

CONCLUSIONS

Three-dimensional numerical experiments of open channel flow with a narrow width and a large roughness factor relative to the water depth were conducted to clarify three-dimensional structures of the flow and the motion of suspended particles. The main conclusions are described as.

1. The flow impinging on the front of the roughening element is divided into the flow that dives into the roughening trough and the flow that overcomes the roughening element, which overlaps with the OSF and BSF, and the secondary flow velocity distribution changes longitudinally.
2. The vertical flow velocity near the sidewall was reduced by particle suspension.
3. Particles ascending near the sidewalls and particles ascending in the center of the channel were observed to ascend while existing in the ascending fluid mass. Ejection was observed around the particles ascending near the center of the channel, while almost no ejection was observed around the particles ascending near the sidewalls, suggesting that the particles near the center of the channel ascend due to ejection, while the particles near the sidewalls ascend under the influence of other factors, such as mean flow. The particles near the sidewalls are thought to rise due to strong the influence of Prandtl's secondary flows of the second kind.

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