# Simulation of Open-Channel Turbulence with Gravel Bed by LES

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## 1 Introduction

Open-channel turbulent flows with rough wall beds have been investigated intensively in the past decades mainly by experimental procedures; however, thanks to the developments of numerical techniques with respect to turbulence modellings and computational resources, simulations of rough wall boundaries came to be possible in recent years (Hurther et al. 2007). In the actual river flow conditions, bottom boundary is a mixture of gravels with various sizes which generates a wide range of separation vortices at the bottom. Among such vortices, those with relatively intense vorticities rise nearer to the water surface and affect water surface fluctuations. However, interrelationship between water surface fluctuations and behaviour to such a near-surface vortex has not been investigated in detail so far both numerically and experimentally, except for an experimental research conducted by Cooper et al. (2006) who examined a relationship between hydraulic resistances and water surface characteristics. In this study, we paid attention to a rough wall flow with randomly distributed gravel particles. At the same time, a new idea of visualizing turbulence structure by tracing a cloud of pseudo-particles repeatedly placed in a horizontal sheet is proposed. The method was applied to simulated results by using a large eddy simulation (LES) model. The water surface was expressed by a density function, thereby air flow phase as well as water flow phase was calculated in the simulation. The bathymetry composed of gravel particles was reproduced by an immersed boundary method (IBM). In the new method, a large number of pseudo-particles are firstly generated in a horizontal sheet moving with their local flow directions.

## 2 Numerical Simulation Model

### 2.1 Basis Equations and boundary treatment

The numerical simulation is based on the large eddy simulation model in a Cartesian grid system. The fundamental equations used after the spatial filtering is as follows:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\overline{u}_i^{n+1} - \overline{u}_i^{n}}{\Delta t} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} - \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial}{\partial x_i}\left\{ \nu_t \left( \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) \right\} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j^2} + f_i \tag{2}$$

Here, $x_i$ is the coordinate in the i-th direction (i=1,2,3), $\overline{u_i}$ is the grid scale velocity in the i-th direction, ν is the kinematic viscosity, $\nu_t$ is the eddy viscosity and $f_i$ is the grid-scale external force in the i-th direction. It should be noted that the unsteady term in the filtered Navier-Stokes equation is discretized by a forward differencing. The bottom gravel boundary was expressed by an immersed boundary (IB) method proposed by Fadln et al. (2000), the direct forcing method, into the LES algorithm. The digital elevation data (DED) of the boundary was obtained by a photogrammetric method using a pair of photographs of randomly distributed gravel particles taken by a high resolution digital camera at two different angles. The LES code was developed so that it can include such a digital bathymetry data as a bottom boundary condition automatically.

### 2.2 SGS Model

In the LES application to complicated boundary configurations, the conventional Smagorinsky's model is difficult to apply, because the damping function used in the model is a function of the distance from the boundary and it is difficult to measure such a distance for a complicated topography. For solving such a problem, we applied the MTS SGS model developed by Inagaki et al. (2002). This model takes into account of the damping effect automatically by using a time scale calculated by the harmonic averaging of the SGS time-scale component and the time scale given by the strain rate. Simulation Condition

The average diameter of gravel particles considered here was 1.5cm. The DED used in the present simulation is shown in Fig.1. Although the individual gravel shape is not completely reconstructed, the random distribution of bottom roughness can be generated fairly well. The number of grid in LES was 85, 100 and 100 in streamwise, transverse and vertical directions, respectively for the gravel bed flow simulation. The number of vertical grid was relatively larger than conventional simulations because the air phase calculation was required in the present LES model. The LES was conducted for the Froude numbers of 0.15, 0.3, 0.4 and 0.6 with a constant water depth of five centimeters. The range of the Reynolds number was between 10,500 and 21,000.

## 3 Discussion

As previously mentioned, water surface fluctuation in turbulent flow are partly caused by impingement of vortices against the water surface. For investigating such a phenomenon, visualization of large-scale turbulence in a horizontal field near the water surface is useful. In the light of this simple idea, we devised a method to use pseudo-particle tracers repeatedly placed in a horizontal plane. In this flow visualization, a large number of pseudo-tracers are firstly generated in a horizontal plane. After the particles are advected with their local velocity vectors, other pseudo-tracers are generated at the same horizontal location. While repeating this procedure at an appropriate frequency, three dimensional coordinates of every

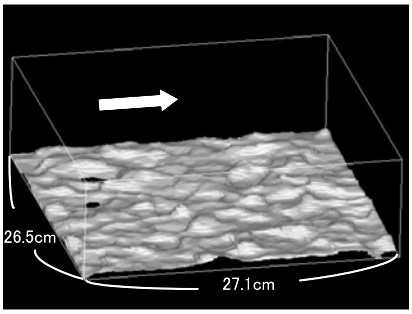
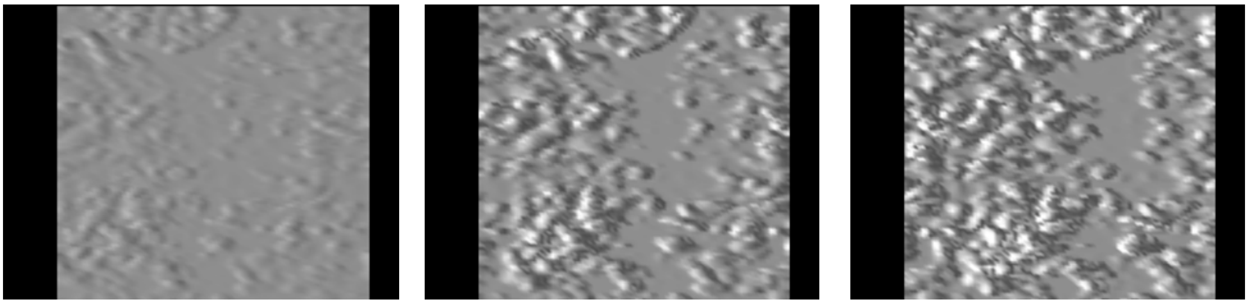
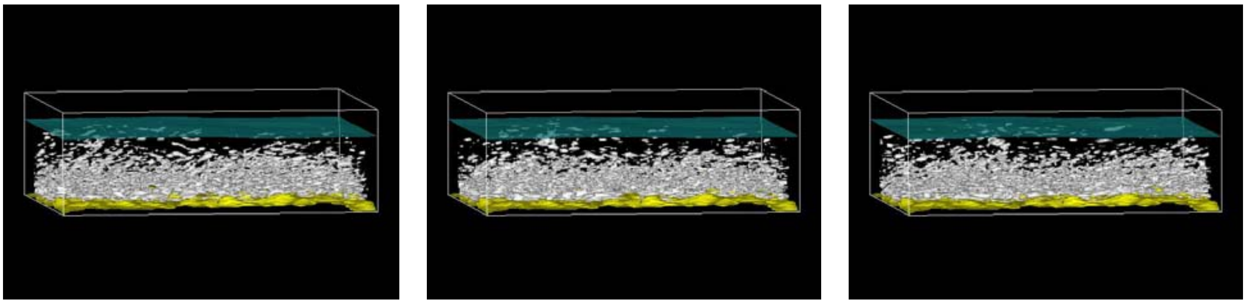


Fig.1 DED for gravel bed



T=0.00 T=0.50 T=1.00

Fig.2 Evolutions of membrane composed of pseudo-particles at $y$=0.8$H$ for Fr=0.6; flow direction is from left to right.



T=0.00 T=0.50 T=1.00

Fig.3 Evolutions birds-eye-view of the second invariant distribution of rate-of-strain tensor for Fr=0.6; flow direction is from left to right.

particle generated at any instance are stored on memory. The specific feature of the method is that the maximum height of the pseudo-particle location at each horizontal coordinates is preserved during the process in order to reveal the effects of upwelling vortices. Therefore, when we view the cloud of particles from above the horizontal plane, some large-scale flow structures become visible as a sort of topographic surface. This visualization method is similar to a hydrogen-bubble technique, in which bubbles are generated in a horizontal membrane. However, it is virtually impossible to conduct such an experiment without disturbing the flow in a physical situation. In the present simulation, 200 by 200 pseudo-particles were traced at every non-dimensional time step of 0.05. As a typical example, the evolution of particle membrane located at $y$=0.8$H$ for the case of the Froude number 0.6 is shown in Fig.2. Here, $H$ is the water depth equal to the height of the liquid phase. The flow direction is from left to right. In this figure, tens of large scale structures emerged from below with time yielding a membrane deformed by numerous bump-like structures. It should be noted that each bump generated by a lump of upwelling fluid has a circular shape, showing that separated fluids moving upwards has a round nose at its tip.

Another feature is that there exists a region where bumps are missing. This indicates there is a structure different in streamwise direction. To clarify this feature, water surface shape is shown in Fig.3 together with the distribution of the second invariant of the rate-of-strain tensor which is a typical quantity that expresses the location of a vortex core. It is clearly seen that the water surface is lowered a little in the downstream region, which corresponds to the region with less bumps. Therefore, we can see that upwelling vortices are reduced where water surface slope has a negative value even if its value is small. The distribution of the second invariant shows vortices generated at the bottom are broken into numerous small parts and some of them are ascending towards the water surface and the number of such vortices are small with negative water slope region, which agree with the visualized results shown in Fig.2.

## 4 Conclusion

By using an LES model capable to treat water surface variations and arbitrary bottom topography with gravel particles, the characteristics of turbulent flow structures were examined by introducing a novel flow visualization method and three-dimensional expressions of water surface and the second invariant values. The commonly observed feature for different Froude numbers, not explained above, is that the size of the bump becomes relatively smaller for a larger Froude number as the Reynolds number also increases for the same condition. The change of the scale should be related to the change of the integral scale of the flow. Another interesting feature made clear in the present simulation was that the scale of each bump visualized in the present method seems comparable to the size of the bottom roughness, which suggests that a lump of fluid separated at each roughness element has reached near the water surface by preserving its relative scale because the water depth is relatively shallow in the present simulation.

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