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Double-averaging analysis of turbulent kinetic energy fluxes and budget based on large-eddy simulation *

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Abstract: The turbulent flow over a channel bed roughened by three layers of closely packed spheres with a Reynolds number of $Re = 15\,000$ is investigated using the large eddy simulation (LES) and the double-averaging (DA) method. The DA velocity is compared with the results of the corresponding laboratory experiments to validate the LES results. The existence of the types of vortex structures is demonstrated by the Q-criterion above the permeable bed. The turbulent kinetic energy (TKE) fluxes and budget are quantified and discussed. The results show that the TKE fluxes are directed downward and downstream near the virtual bed level. In the TKE budget, the form-induced diffusion rate is significant in the vicinity of the crest bed level, and the TKE production rate and the dissipation rate attain their peaks at the crest bed level and decrease sharply below it.

Key words: Large eddy simulation (LES), turbulent kinetic energy (TKE) fluxes, turbulent kinetic energy budget, double-averaging analysis

Introduction

The study of the turbulent flow over a permeable bed is considered to be highly important in the hydraulic engineering. Although nearly all natural channels have permeable beds such as gravel-bed rivers, very little research effort was taken to study the effect of the channel bed permeability on the mean and instantaneous flows, especially the turbulent kinetic energy fluxes and budget, which play dominant roles in the overall structure of the mean near-bed turbulence of permeable bed flows.

In most studies, the time-averaging assumptions are modified and applied in the vicinity of the rough beds, in which the time-averaged flow is locally three-dimensional and heterogeneous in space. To resolve the spatial heterogeneity, the double-averaging (DA) method is adopted, where the time-averaging of Navier-Stokes equation is supplemented by the space averaging. The DA method potentially offers new insights into the effects of the macro-roughness element on the mean benthic hydrodynamics, particularly, when it is combined with a local flow analysis. This method was originally developed for atmospheric boundary layer studies[1] and was applied by Ojha and Mazumber[2]. They carried out the averaging of the time-averaged velocity along the lines of constant distance from a wavy bed. The work of Nikora et al.[3], which is revisited in the framework of river hydraulics, consists of averaging the Navier-Stokes equations in time and space over an area contained in a plane parallel to the flow direction. In addition, the double-averaging is also applied to the fluid momentum equations and the advection-diffusion equations. Dey and Das[4] and Mignot et al.[5] examined the DA Reynolds shear stress (RSS), the turbulent kinetic energy (TKE) flux, and the budget in the flows over a bed of angular crushed stones.

However, in a layer near the rough bed, the flow is extremely heterogeneous, which increases the difficulty of measuring accurately the flow quantities.

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Additionally, the DA method remains severely limited due to the lack of measuring tools that can provide a large-scale and three-dimensional turbulent structure. Therefore, a numerical model is an important tool to improve understanding of the physics of these complex flow dynamics. In the traditional numerical simulation, the Reynolds-averaged Navier-Stokes model is applied widely[6]. But the vortex or the instantaneous quantities can not be obtained. The large-eddy simulation (LES) is a more advanced approach in the computational fluid dynamics. Stoesser and Nikora[7] performed an LES of the turbulent flow over square ribs mounted on the wall. Fang et al.[8] calculated the non-submerged groin flow in a shallow open channel by using the LES.

To understand turbulence, many researchers focused on the TKE budget and fluxes, as the key indices for understanding the turbulence processes and scales throughout the water column. Most open-channel studies locate the maximum TKE production and turbulent diffusion at the bed[9-11]. However, Bagherimiyab and Lemmin[12] showed that the peak of the turbulence activity occurs in the vicinity of the canopy crest. The differences are mainly due to the resolution close to and within the roughness elements. Additionally, Dey and Das[4] indicated that the fluxes directed downward and downstream are composed of sweep events, and an upstream transport of the TKE fluxes in the upper layer of the flow is due to the inertia of the fluid streaks. However, few studies[13,14] measured the mean TKE fluxes oriented towards the bed in the inner flow region defined as $z/h < 0.2$. Therefore, further investigations of the TKE budget and fluxes in the turbulent flow over a permeable bed are desirable.

This paper first introduces the DA method for the analysis of the turbulent characteristics near and above the roughness bed. Because the flow within and over a permeable bed is not fully understood, the LES model is used to explore the flows, especially, the TKE fluxes and the TKE budget. The model is validated by several experiments, with a good agreement. The existence of vortex structures is demonstrated. It is shown that near the virtual bed level, the form-induced diffusion rate is significant. The TKE production and the dissipation rate attain peaks at the crest bed level.

1. DA method and numerical model

1.1 *DA method*

The DA method involves the time averaging conceptually supplemented by the area averaging in the layer parallel to the mean bed surface. In a traditional Reynolds decomposition, the local instantaneous flow quantity $\boldsymbol{\theta}$ can be decomposed as follows

$$\boldsymbol{\theta} = \bar{\boldsymbol{\theta}} + \boldsymbol{\theta}' \tag{1}$$

where $\bar{\boldsymbol{\theta}}$ is the local time-averaged flow quantity and $\boldsymbol{\theta}'$ is the fluctuations of the local instantaneous flow quantity $\boldsymbol{\theta}$ from the local time-averaged flow quantity $\bar{\boldsymbol{\theta}}$. Additionally, in the DA method, the local time-averaged flow quantity is decomposed as follows

$$\bar{\boldsymbol{\theta}} = \left\langle \bar{\boldsymbol{\theta}} \right\rangle + \tilde{\boldsymbol{\theta}} \tag{2}$$

where $\tilde{\boldsymbol{\theta}}$ is the fluctuations of the local time-averaged flow quantity $\bar{\boldsymbol{\theta}}$ from the DA flow quantity $\left\langle \bar{\boldsymbol{\theta}} \right\rangle$. Below the roughness crest, the roughness geometry function $\phi(z)$ is used in the DA equations, $\left\langle \bar{\boldsymbol{\theta}} \right\rangle_s = \phi \left\langle \bar{\boldsymbol{\theta}} \right\rangle$.

1.2 *Governing equations and subgrid-scale modeling*

In the LES model, the eddies larger than the grids are resolved, while the eddies smaller than the grids are modeled. The Navier-Stokes continuity and momentum conservation equations for the incompressible flow without consideration of the density variation can be written as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{3}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = g_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} \tag{4}$$

where $i, j \in [1,2,3]$, u_i is the component of the velocity vector $\boldsymbol{u}$, p is the pressure, ν is the kinematic viscosity of the fluid, and g_i is the ith component of the gravity acceleration. To simplify these nonlinear equations, it is assumed that the pressure contains two parts: $p = p_s + p_d$, where p_s is the hydrostatic pressure, and p_d is the dynamic pressure. Then

$$g_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} = \frac{1}{\rho}\frac{\partial p_s}{\partial x_i} - \frac{1}{\rho}\frac{\partial (p_s + p_d)}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p_d}{\partial x_i} \tag{5}$$

For convenience, we use p to mean p_d in the following discussions. The equations are normalized by the water depth H, the bulk velocity U and the reference pressure ρU^2. Then, they are filtered with