

Comparative Assessment of Inflow Turbulence Generation Methods and Subgrid-Scale Models for Large Eddy Simulation of Turbulent Flow over Hilly Terrain

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SUMMARY

The performance of inflow turbulence generation methods and subgrid-scale (SGS) models are crucial for accurate prediction of turbulent flow over hilly terrain using large eddy simulation (LES). In this study, two types of inflow generation methods, the wind tunnel replication method and the synthetic turbulence generation method, are examined. In addition, two types of SGS models, the standard Smagorinsky model and the coherent structure Smagorinsky model, are considered. The advantages and limitations of different inflow turbulence generation methods and SGS models are discussed in terms of flow patterns and turbulent statistics. These findings provide valuable guidance for selecting appropriate LES modeling strategies, thereby improving both the physical reliability of turbulence simulations and their applicability to engineering applications in complex terrain scenarios.

Keywords: *inflow turbulence generation, subgrid-scale model, large eddy simulation, turbulent flow, hilly terrain*

1. INTRODUCTION

Prediction of turbulent flow characteristics over hilly terrain is essential for various engineering applications, including wind resource assessment, wind load assessment and air pollutant dispersion. However, atmospheric boundary layer (ABL) flows over complex terrain exhibit intricate dynamics, such as turbulence intermittency, flow separation and reattachment (Yang et al., 2021; Zhou and Ishihara, 2025).

With the continuous advancement of computational resources, large eddy simulation (LES) has emerged as a powerful approach for predicting turbulent flows over hills, serving as an effective complement to wind tunnel experiments. The accuracy of LES is highly dependent on two aspects: the inflow turbulence generation method and the subgrid-scale (SGS) model.

The wind tunnel replication method and synthetic turbulence method are two widely used approaches for generating inflow turbulence. The former method can accurately reproduce turbulent boundary layer when detailed experimental conditions are available and fine mesh resolution is employed. However, this approach is inherently time-consuming and computationally demanding. In contrast, synthetic turbulence methods are more computationally efficient but struggle to preserve realistic turbulence structures within the computational domain due to incompatibility with the Navier–Stokes equations. Nevertheless, the comparative evaluation of inflow turbulence generation technique has rarely been conducted in the context of turbulent flows over hilly terrain.

With respect to the SGS modeling, the Smagorinsky-based models are commonly employed in computational wind engineering. In addition, the coherent-structure Smagorinsky model

(Kobayashi, 2005) has been demonstrated improved performance in many turbulent flow problems. Nonetheless, its applicability has barely been examined in the hill-induced flows.

This study aims to systematically assess the performance of inflow turbulence generation methods and SGS models in predicting turbulent flows over a smooth two-dimensional (2-D) ridge and a three-dimensional (3-D) hill.

2. NUMERICAL MODEL

2.1. Governing Equations

The spatially filtered governing equations for continuity and momentum are written as:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial(\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

where \tilde{u}_i and \tilde{u}_j are the velocity components, \tilde{p} and ν are the pressure and viscosity, respectively. The tilde denotes the spatial filtering operator. The term τ_{ij} stands for the SGS stress, which can be approximated based on the Boussinesq eddy-viscosity hypothesis:

$$\tau_{ij} = -2\nu_t \tilde{S}_{ij} + \frac{1}{3} \tau_{kk} \delta_{ij} \quad (3)$$

where \tilde{S}_{ij} is the filtered strain-rate tensor and ν_t is the SGS eddy viscosity, which is defined as:

$$\nu_t = [C_s \Delta]^2 |\tilde{S}| \quad (4)$$

where the Smagorinsky constant C_s is set to 0.1 for the standard Smagorinsky model, while it is determined by the following formulations for the coherent structure Smagorinsky model:

$$C_s = (C_1 |F_{CS}|^{3/2} F_\Omega)^{1/2}, F_{CS} = \frac{Q}{E}, F_\Omega = 1 - F_{CS} \quad (5)$$

$$Q = \frac{1}{2} (\overline{W_{ij} W_{ij}} - \overline{S_{ij} S_{ij}}), E = \frac{1}{2} (\overline{W_{ij} W_{ij}} + \overline{S_{ij} S_{ij}}) \quad (6)$$

where C_1 is the model constant ($C_1 = 1/22$), F_{CS} is the coherent structure function defined as the second invariant Q normalized by the velocity gradient magnitude E in a grid-scale flow field, and F_Ω is the energy decay suppression function.

2.2. Computational Domain and Mesh

For the wind tunnel replication method, the turbulent boundary layer is generated using cubic roughness blocks identical to those employed in the wind tunnel experiment of Ishihara and Hibi (1999). The computational domain spans $(L_x, L_y, L_z) = (9, 0.66, 0.6)m^3 = (225, 16.5, 15)h^3$, as shown in Figure 1. The geometric shape of the 2-D ridge and the 3-D hill are prescribed as: $z_s(x, y) = h \cos^2(\pi x / 2L)$ and $z_s(x, y) = h \cos^2[(x^2 + y^2)^{1/2} / 2L]$, respectively. The hill height and width are set as $h = 0.04m$ and $L = 0.1m$. For the synthetic turbulence method, the computational domain covers $(L_x, L_y, L_z) = (2, 0.66, 0.6)m^3 = (50, 16.5, 15)h^3$. To accurately

resolve the terrain-induced flow dynamics, the local grid refinement together with a body-fitted grid arrangement is adopted in the vicinity of the topography. The horizontal grid resolution $\Delta x/h = 0.05$ and $\Delta y/h = 0.125$ is employed to achieve an optimal trade-off between computational accuracy and efficiency. Moreover, the first-layer grid spacing in the vertical direction is specified as $\Delta z/h = 0.0125$. The total mesh number is approximately 15.74 million for the wind tunnel replication method and 5.11 million for the synthetic turbulence method.

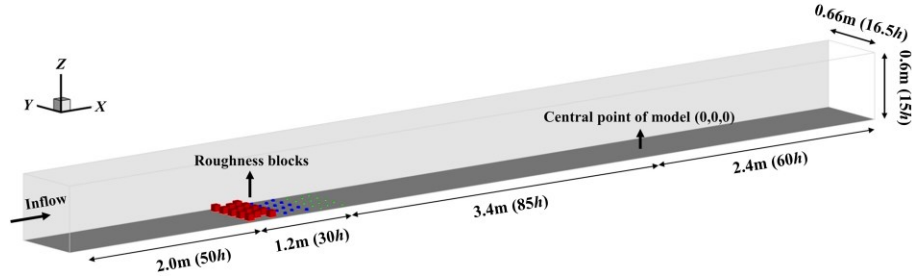


Figure 1: Computation domain for the wind tunnel replication method.

3. RESULTS AND DISCUSSIONS

3.1 Flow Patterns

Figure 2 shows the instantaneous vorticity contour and mean velocity streamline at the $y = 0$ plane over the 2-D ridge predicted by LES using the wind tunnel replication method and the synthetic turbulence method. A larger number of smaller-scale, higher-intensity vortices are generated in the wake of the 2-D ridge when using the wind tunnel replication method, particularly in the region far above the ground. This difference can be attributed to the absence of coherent, fully developed turbulence structures in the incoming flow produced by the synthetic turbulence method. However, the time-averaged separation bubble predicted by two approaches show good agreement.

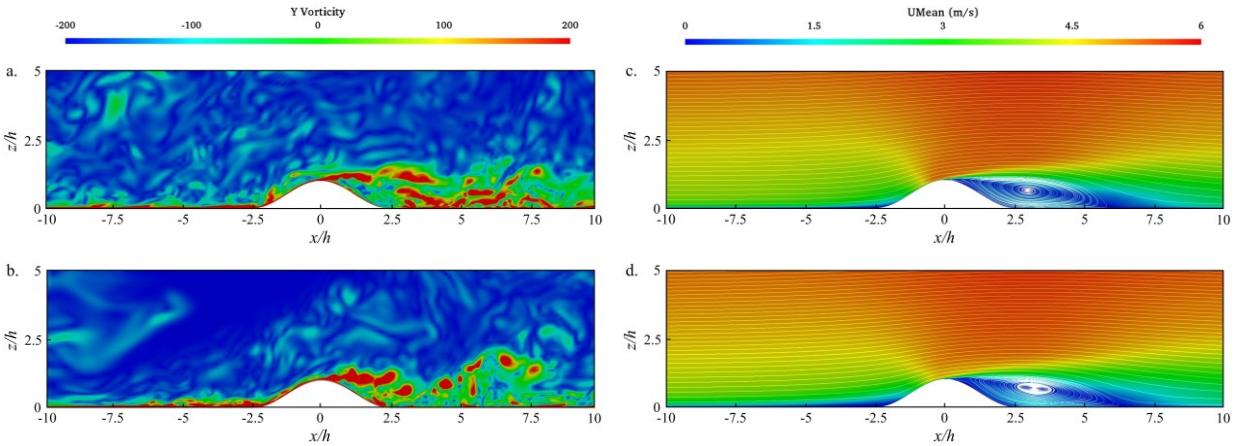


Figure 2: Comparison of instantaneous vorticity contour and mean velocity streamline over the 2-D ridge using (a, c) wind tunnel replication method and (b, d) synthetic turbulence method.

3.2 Turbulent Statistics

Figure 3 presents the vertical profiles of mean velocity and turbulence intensity over the 2-D ridge predicted by LES using the wind tunnel replication method and the synthetic turbulence method.

Although slight discrepancies on the upstream hillslope, the mean velocity profiles obtained with the two inflow turbulence generation techniques agree well with the experimental measurements, as shown in Figure 3(a). On the other hand, more pronounced differences are observed in the predicted turbulence intensity, with notable deviations between the wind tunnel replication method and the synthetic turbulence method, as illustrated in Figure 3(b).

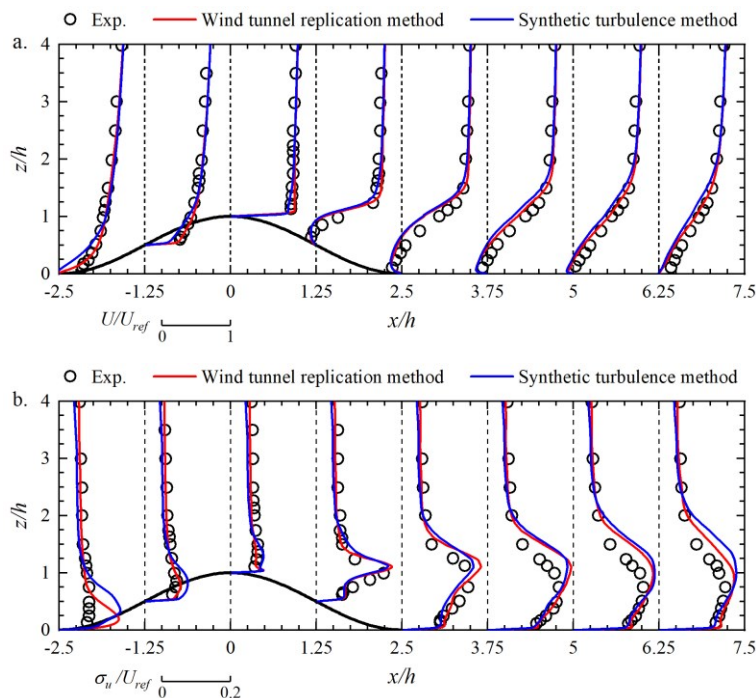


Figure 3: Distributions of mean velocity deficits in inversion-capped neutral and convective boundary layers.

4. CONCLUSIONS

In this study, LES simulations are conducted to investigate turbulent flow over a smooth 2-D ridge and 3-D hill. The capabilities of two inflow turbulence generation techniques and SGS models are comprehensively evaluated in the context of flow pattern, mean velocity, turbulence intensity and velocity spectra. Overall, the wind tunnel replication method combined with the standard Smagorinsky model provides more accurate predictions of the flow pattern, turbulence intensity and velocity spectra over hilly terrain.

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